1999

Analysis of radio frequency components for shipboard wireless networks

Matthews, Mark M.

Monterey, California: Naval Postgraduate School

http://hdl.handle.net/10945/13458

NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

ANALYSIS OF RADIO FREQUENCY COMPONENTS FOR SHIPBOARD WIRELESS NETWORKS

by

Mark M. Matthews

December 1999

Thesis Advisor: Xiaoping Yun

Approved for public release; distribution is unlimited

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE December 1999	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE ANALYSIS OF RADIO FREQUENCY COMPONENTS FOR SHIPBOARD WIRELESS NETWORKS	5. FUNDING NUMBERS
6. AUTHOR(S) Mark M. Matthews	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

Computers and computer networks are generally viewed as tools that allow personnel to increase productivity. However, due to the limitations of traditional local area networks (LANs), the navy has not been able to efficiently leverage commercial computer technology for general shipboard applications. Recent advances in wireless LANs (WLANs) now permit mobile users to employ network applications to manage and share information. Mobile computers can be used by the crew to supplement damage control reports and reduce the strain on the over-taxed voice circuits. Watchstanders can make log entries into a central data base that utilizes automated data trend analysis algorithms to detect deteriorating components and schedule maintenance to correct the problem prior to component failure. The advantages to using WLANs onboard naval vessels are nearly endless.

This thesis evaluates commercially available wireless networking components for use onboard naval vessels. Installing such equipment would enable mobile watchstanders to access services provided on LANs. The theories and principles governing the operation of WLANs are discussed. Then, current commercially available components are evaluated in a laboratory setting. Finally, the most promising component evaluated is tested in the hangarbay of an aircraft carrier and throughout the inhabitable compartments of a Los Angeles class submarine.

14. SUBJECT TERMS Wireless Local Area Networks, Spread Spectrum, Mobile Computers			15. NUMBER OF PAGES 102
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

THIS
PAGE
IS
MISSING
IN
ORIGINAL
DOCUMENT

THIS PAGE INTENTIONALLY BLANK

ANALYSIS OF RADIO FREQUENCY COMPONENTS FOR SHIPBOARD WIRELESS NETWORKS

Mark M. Matthews
Lieutenant, United States Navy
B.S., United States Naval Academy, 1992

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE
IN
ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1999

Author: [redacted]
Mark M. Matthews

Approved by: [redacted]
Xiaoping Yun, Thesis Advisor

[redacted]
John McEachen, Second Reader

[redacted]
Jeffrey Knorr, Chairman
Department of Electrical and Computer Engineering

THIS PAGE INTENTIONALLY BLANK

ABSTRACT

Computers and computer networks are generally viewed as tools that allow personnel to increase productivity. However, due to the limitations of traditional local area networks (LANs), the navy has not been able to efficiently leverage commercial computer technology for general shipboard applications. Recent advances in wireless LANs (WLANs) now permit mobile users to employ network applications to manage and share information. Mobile computers can be used by the crew to supplement damage control reports and reduce the strain on the over-taxed voice circuits. Watchstanders can make log entries into a central data base that utilizes automated data trend analysis algorithms to detect deteriorating components and schedule maintenance to correct the problem prior to component failure. The advantages to using WLANs onboard naval vessels are nearly endless.

This thesis evaluates commercially available wireless networking components for use onboard naval vessels. Installing such equipment would enable mobile watchstanders to access services provided on LANs. The theories and principles governing the operation of WLANs are discussed. Then, current commercially available components are evaluated in a laboratory setting. Finally, the most promising component evaluated is tested in the hangarbay of an aircraft carrier and throughout the inhabitable compartments of a Los Angeles class submarine.

THIS PAGE INTENTIONALLY BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The author would like to acknowledge the financial support of the New Attack Submarine Program, PMS450T2, and the Naval Sea Systems Command in sponsoring the research involved.

The author would like to thank Professors Xiaoping Yun and John McEachen for their guidance and support during this research effort. Additional thanks is extended to Dennis Volpano and Clark Robertson for their help. Also, the author would like to thank the crewmembers of the USS TRUMAN (CVN 75) and the USS MEMPHIS (SSN 691) for their assistance in evaluating commercially available products.

Finally, the author would like to thank his wife, Jennifer, and son, Samuel, for their enduring patience and understanding.

THIS PAGE INTENTIONALLY BLANK

I. INTRODUCTION

Several current programs involve increasing personnel efficiency and improving internal communication systems onboard naval vessels. As the ships of the navy become more technologically advanced, crew members are reaching their limits of information processing and handling. The usual answer to information problems is to increase the utilization of computers and to provide software tailored to the user's needs. This solution is easy if the targeted environment is a comfortable office; however, the crew members of a naval vessel demand mobility. The recent advances in wireless networking capabilities now offer a solution for mobile clients. These commercially available products must be evaluated for feasibility of employment onboard navy ships.

This thesis serves as part of an ongoing examination of the feasibility of shipboard wireless networks. Other works contributing to this project include the Feasibility Analysis for a Submarine Wireless Computer Network Using Commercial off the Shelf Components by Steven M. Debus and Distributed Software Applications in Java for Portable Processors Operating on a Wireless LAN by Kurt J. Rothenhaus. The focus of this thesis is to provide a comparative performance analysis of the varying types of commercially available, radio frequency components for wireless networks.

A. THE INFORMATION AGE

Computers have permeated into almost every facet of our daily existence. Initially, computers were only found in large business organizations. Users would need to schedule time

during which the company's computer was dedicated to their tasks. With technological advances, these few mainframes gave way to workstations and desk tops. Users now had computers at their disposal throughout the day. However, to share information, a user would generally have to transfer data to a floppy disk and physically transport it to another location. To enable a more efficient transfer of information from one computer to the next, computer communication systems were developed and the local area network (LAN) was born. [Ref. 1]

The goal of each step in the march of computer technology was to enable a more efficient means to share information. With LANs, members of integrated product teams with diverse functional backgrounds could concurrently contribute to product designs. Thus, the required development time could be reduced and potential problems could be identified and corrected prior to initial production. However, due to constraints in mobility, some production team members were left out. The physical constraints of providing a power supply and a network connection made it impractical for personnel requiring mobility to utilize computers. Laptop computers, which functioned great for business travelers, did not provide a complete solution. Only recently, with the introduction of portable computers and wireless networking has the computer industry provided viable solutions for mobile users.

B. THE WIRELESS NETWORKING WORLD

The commercial computer industry has developed several products as solutions for mobile network clients. Computer devices can be purchased off the shelf or made to order to incorporate specialized functions. A variety of networking components are offered including

high speed infrared links, radio frequency modems, and even smart phones which incorporate limited Internet services to cellular clients.

These commercial devices are tailored to function in a range of environments. The earliest components were designed for use in factories and assembly lines. Most were hardened to provide some protection versus the industrial environment in which they were used, and were limited in functionality as the goal was solely to collect and share information. Since then, the distinction between mobile computing and conventional methods has blurred. Now, portable computers are becoming more prevalent and wireless networks are being installed in offices. Wireless networks are being used as adjuncts to conventional LANs for a variety of reasons. Some businesses that require frequent office reconfiguration save money by using wireless components in addition to a hard-wired network backbone. Other businesses find it undesirable to run the cabling required for conventional LANs. Overall, most commercial components are designed for office or light industrial environments.

Unfortunately, the office or light industrial environment description does not apply to shipboard compartments. Onboard ship, the passageways are more narrow and the conditions are more harsh. Portable computers must be able to withstand some reasonable impacts with hard surfaces and light exposure to water and oil. Additionally, the wireless networking transmitters must be robust enough to overcome the effects of a severe multipath environment consisting largely of metal surfaces. All of these features must be offered at an affordable price to provide the navy with a feasible means to incorporate wireless networking into everyday shipboard life.

C. GOAL FOR THIS THESIS

The goal of this thesis is to determine which commercially available wireless networking components best meet the needs of tomorrow's navy. First, the principles involved with wireless networking will be examined. Then, several diverse components will be purchased and evaluated in a laboratory environment. After comparative analysis, the best performing component will be evaluated in a variety of shipboard environments.

D. THESIS OUTLINE

This thesis is organized as follows. Chapter II discusses the radio frequency characteristics of the shipboard environment. Chapter III discusses the current transmission schemes used by commercially available wireless networking components. Next, the computer related principles of wireless networking are discussed as Chapter IV compares the protocols used in wireless networks to those used in common Ethernet LANs. Chapter V describes the laboratory testing and determines which of the products evaluated offers the most promising solution for the wireless networking needs of the navy. Chapter VI describes the field testing conducted. In conclusion, Chapter VII summarizes the feasibility of employing commercially available products for wireless networking in the navy.

II. CHARACTERISTICS OF THE SHIPBOARD RF CHANNEL

Typical communication system analysis begins with certain assumptions of the channel characteristics. In the most trivial cases, the channel is assumed to exhibit additive white Gaussian noise (AWGN) characteristics. In these cases, the transmitted signal experiences only free space loss, which is proportional to the square of the distance between the transmitter and receiver for a given frequency. With the only interference at the receiver being caused by statistically independent Gaussian variation in antenna and thermal noise, the engineer needs only increase the bit energy of the transmitted signal to improve system performance. Moving such a system from free space into a shipboard environment invalidates many of the assumptions that simplified the channel characteristics.

A. CHANNEL CHARACTERISTICS

Initially it was assumed that the received signal consisted solely of a direct path component. Onboard ship, there are many surfaces that preclude direct path propagation and promote multipath signal reception. Figure 2.1 illustrates typical geometries that produce different signal path receptions. The presence of the multipath components greatly complicates analysis and degrades channel performance.

1. The AWGN Channel

Consider the diagram shown in Fig. 2.1a, which illustrates a communication channel comprised solely of a direct path component. For a given transmitted signal

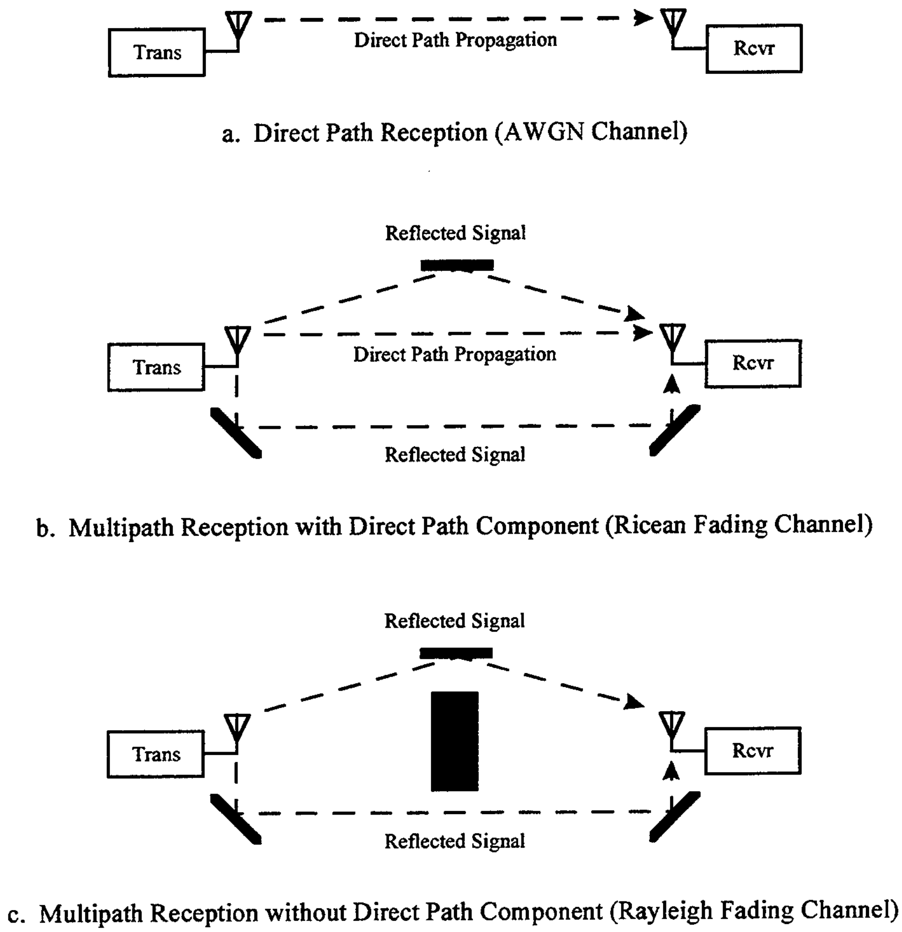


Figure 2.1: Channel Reception Path Models

$$s(t)=\mathrm{Re}\left(u(t)\cdot e^{j\omega_c t}\right) \qquad [2.1]$$

the received signal can be expressed as

$$r(t)=\alpha(t)\cdot s(t) \qquad [2.2]$$

where $\alpha(t)$ is a function that describes the attenuation experienced between the transmitter and receiver [Ref. 2]. In such a geometry the attenuation function would usually be considered constant, not time varying. However, to account for mobility of transmitter or receiver, it is expressed generally as a function of time. Channel performance analysis using this expression for the received signal is trivial.

2. Fading Channels

A general expression for the received signal for a channel with multipath reception either with or without a direct path component can be expressed as

$$r(t)=\sum_{n}\alpha_n(t)\, s\left[t-\tau_n(t)\right] \quad . \qquad [2.3]$$

Where $\alpha_n(t)$ represents the attenuation experienced by the nth reception and $\tau_n(t)$ represents the delay in reception due to variation in propagation distance. The low pass equivalent of the received signal can be expressed as

$$r_{lp}=\sum_{n}\alpha_n(t)\, u\left[t-\tau_n(t)\right] e^{-j\omega_c \tau_n(t)} \quad . \qquad [2.4]$$

It is apparent from Eq. 2.4 that multichannel propagation effects not only the received signal amplitude but also the received phase. Because of phase variation, each reception will constructively or destructively combine to form the received signal. This phase fluctuation produces a phenomenon called signal fading. [Ref. 2]

It can be shown that the received signal amplitude resembles a Ricean random variable for those geometries that permit a direct path component and a Rayleigh random variable for those that do not. Thus, these channels are referred to as Ricean or Rayleigh fading channels, depending upon the presence or absence of a direct path component. Because direct path propagation rarely exists in a shipboard environment and because Rayleigh fading channels offer worst-case performance, the shipboard RF channel is characterized as a Rayleigh fading channel.

B. EFFECTS OF RAYLEIGH FADING CHANNELS

Fading channels effect signal propagation in several ways. Figure 2.2 separates these effects into two main categories: large scale fading and small scale fading.

1. Large Scale Fading

Large scale fading, largely dependent upon the geography of the region between the transmitter and receiver, provides a means to account for the signal attenuation due to obstructions. The average path loss in decibels for a channel with large scale fading can be expressed as

$$\left[L_p(d)\right]_{dB} = \left[L_s\left(d_0\right)\right]_{dB} + 10\,n\cdot\log\left(\frac{d}{d_0}\right) \qquad [2.5]$$

where d_0 is a reference distance (typically one meter for indoor environments), $[L_s(d_0)]_{dB}$ is free space loss in decibels for the reference distance, and n is a parameter dependent upon the effects of the obstructions on the signal propagation. For path loss at a specific distance for a specific environment, an additional term, X_σ, is added to the equation.

$$\left[L_p(d)\right]_{dB} = \left[L_s\left(d_0\right)\right]_{dB} + 10\,n\cdot\log\left(\frac{d}{d_0}\right) + X_\sigma \qquad [2.6]$$

X_σ is a zero-mean Gaussian random variable with a standard deviation of σ that accounts

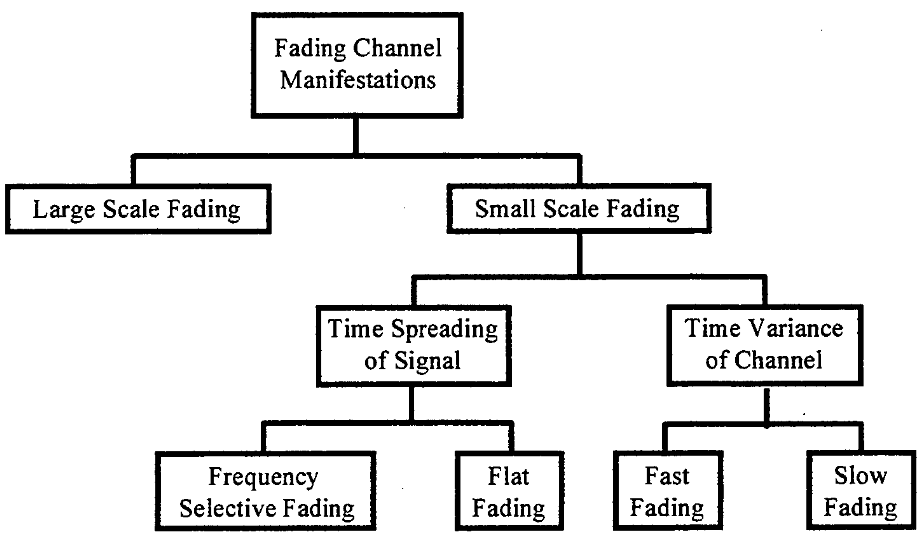


Figure 2.2: Fading Channel Effects After Ref. [3]

for variations about the average path loss for a specific environment. [Ref. 3]

While large scale fading causes degradation of signal reception, it is easily countered. Simply including an approximation of expected or worst-case large scale fading attenuation in the link budget analysis will mitigate its effects.

2. Small Scale Fading

As illustrated in Fig. 2.2, the effects of small scale fading are manifested in two forms: time spreading of the signal and time variance of the channel. The time spreading of the signal can produce either frequency selective or flat fading while the time variance of the channel can cause either fast or slow fading.

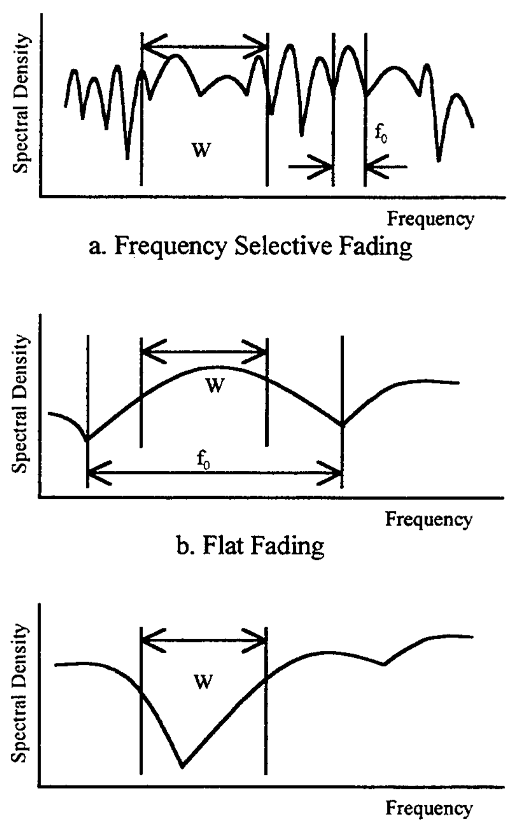
a) Time Spreading of the Signal

As shown in Eq. 2.3, each multipath reception experiences a different delay time causing a time spreading of the received signal. As long as the multipath receptions occur during the duration of the transmitted symbol, the channel is said to experience flat fading. However, when multipath receptions overflow into subsequent symbol periods, channel induced intersymbol interference (ISI) occurs causing frequency selective fading. This occurrence is best illustrated in the frequency domain where the coherence bandwidth of the channel, f_0, is proportional to the maximum delay time difference experienced by multipath receptions. Using W to indicate signal bandwidth, Fig. 2.3 illustrates the difference between frequency selective and flat fading. It is important to note that, while flat fading is more desirable than frequency selective fading, a flat fading channel can still experience signal

degradation when the frequency characteristics of the channel contain a null in the signal's frequency band. This occurrence, called deep fading, is shown in Fig. 2.3c. [Ref. 3]

b) Time Variation of the Channel

Relative motion between the transmitter and receiver causes the propagation paths of the multipath receptions to change. This results in variations in the amplitude and phase of the received signal. The coherence time of the channel is the measure of time during which the channel's characteristics are constant. Because the channel's characteristics are



a. Frequency Selective Fading
b. Flat Fading
c. Flat Fading with Channel Null

Figure 2.3: Frequency Selective and Flat Fading After Ref. [3]

largely dependent upon the current multipath receptions, the coherence time can be thought of as a period during which the multipath receptions are constant. Thus, it is apparent that the coherence time is dependent upon the velocity of the transmitter and receiver and the topography of the environment. When the coherence time is greater than the transmitted symbol duration, the channel is a slowly fading channel. When the symbol duration is significantly greater than the coherence time of the channel, the channel characteristics will change several times during the symbol transmission. This fluctuation in channel characteristics, called fast fading, causes signal degradation due to ISI much like that experienced in frequency selective fading. [Ref. 3]

C. CLASSIFICATION OF THE SHIPBOARD RF CHANNEL

Given that the communications systems analyzed in this thesis transmit data at a rate of either 1 Mbps or 2 Mbps, it is easy to determine if the channel will exhibit frequency selective or flat fading. Because the shift in data rate is achieved through changing between two level and four level modulation for the components evaluated, the symbol period for any data rate can be found as

$$T_s = \frac{1}{R_s} = \left(\frac{1}{R_b}\right)\cdot\left(\frac{\text{bits}}{\text{symbol}}\right) = \left(\frac{1}{1\ \text{Mbps}}\right)\cdot\left(\frac{1\ \text{bit}}{1\ \text{symbol}}\right) = 1\ \mu\text{sec}\,. \qquad [2.7]$$

Comparison of symbol period to multipath reception delay time determines whether the channel exhibits frequency select or flat fading. For flat fading, where the delay of the multipath receptions does not introduce ISI, the following relationship must exist

$$T_s >> \tau_n \quad . \qquad [2.8]$$

Applying the convention that an order of magnitude satisfies "much greater than" requirements yields

$$\tau_n < \frac{1}{10}\ \mu\text{sec} \qquad [2.9]$$

for flat fading channels. With the delay being introduced by a difference in propagation distance, a maximum differential propagation distance is determined as

$$\delta d_{max} = \tau_n \cdot c = (0.1\ \mu\text{sec})\left(3 \cdot 10^8\ \frac{\text{m}}{\text{sec}}\right) = 30\ \text{m} \quad . \qquad [2.10]$$

In an indoor environment such as a compartment on a submarine, several reflections between the transmitter and receiver would be required to exceed this thirty meter value. The signal attenuation due to these reflections would prevent that reception from being detected at the receiver. Thus, it can be assumed that all channel receptions will essentially occur within one symbol period and the channel will exhibit flat fading characteristics. [Ref. 2]

For slow fading vs. fast fading determination, the symbol period is compared to the coherence time of the channel, Δt_c. For slow fading, the following relationship must be met

$$T_s \ll \Delta t_c \ . \qquad [2.11]$$

Applying the order of magnitude requirement for the "much less than" relationship produces the following minimum coherence time for a slow fading channel with the symbol period determined in Eq. 2.7.

$$\Delta t_c > 10 \ \mu\text{sec} \qquad [2.12]$$

Recall that the coherence time is a measure of time during which the channel's characteristics are constant. These characteristics are largely dependent upon the geometry between the transmitter and receiver. A slowly moving transmitter and receiver, compared to the symbol rate, should produce a slowly varying channel. The shipboard RF channel should, therefore, exhibit slow fading characteristics. [Ref. 2]

D. SYSTEM PERFORMANCE IN FADING CHANNELS

Now that the effects of multipath channel propagation on a transmitted RF signal have been discussed, it is important to investigate the degradation that multipath fading has on system performance. Figure 2.4, showing bit error probability (P_b) as a function of bit energy per noise power spectral density (E_b/N_0) for channels of various characteristics, illustrates the degradation in system performance due to multipath fading for a typical modulation technique. The lower curve, exhibiting the lowest P_b for a given E_b/N_0, is the performance expected from a system operating in an AWGN channel. The upper curve represents system performance in

the presence of ISI induced by fast or frequency selective fading. The middle curve represents the Rayleigh limit, or the best performance for a system using a typical modulation scheme in the presence of slow, flat fading. It is obvious from Fig. 2.4 that the performance of the fast or frequency selective channel is not acceptable. Additionally, the marginal improvement offered by the Rayleigh limit is not sufficient to meet the bit error probability demands of anything more than the simplest communication system. Therefore, the communication system must be enhanced to mitigate performance degradation due to multipath fading.

Given that the communication channel exhibits flat, slowly fading characteristics, efforts to improve system performance focus on mitigation of the effects of the deep fading phenomenon. Typically, this is accomplished by using spread spectrum modulation and by providing diversity.

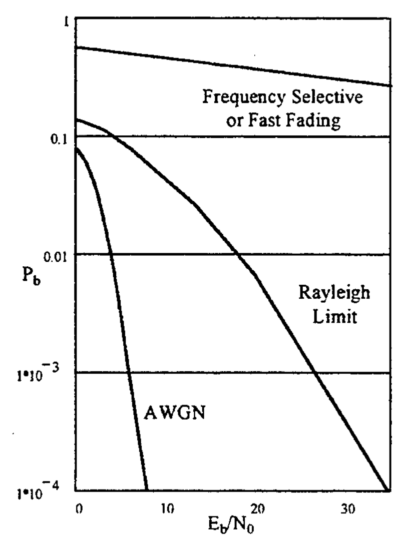


Figure 2.4: System Performance After Ref. [4]

The most prominent method used to minimize susceptibility to deep fading is spread spectrum modulation. Currently, two forms of spread spectrum modulation are used in wireless networking: direct sequence and frequency hopping. These forms of spread spectrum communications and their application in wireless networking are explained in detail in the next chapter.

Diversity offers a means to improve communications reliability in fading channels. By independently transmitting or receiving multiple copies of a symbol, the probability of error free reception is improved. In other words, averaging with other independent receptions mitigates the effects of a specific deep fade reception. At the transmitter, diversity can be provided in either time or frequency but neither offers a viable means to improve performance. Time diversity is implemented by sequentially transmitting multiple copies of a symbol, requiring a reduction in effective symbol rate. Frequency diversity requires joint transmission of the signal at different carrier frequencies, increasing the bandwidth and complexity of the transmitter. Diversity at the receiver, consisting of spatial or polarization diversity is easier to provide. Spatial diversity requires multiple antennas physically separated to provide independent signal reception. Polarization diversity consists of designing antennas to receive independent receptions based upon polarization of the received signal. It is easy to realize that diversity at the receiver is constrained by the size of the receiving unit in relation to the wavelength of the transmitted signal. For small, inexpensive, commercially available RF components, diversity alone cannot provide adequate deep fade mitigation but must be used in conjunction with spread spectrum modulation. [Ref. 4]

III. SPREAD SPECTRUM COMMUNICATIONS SYSTEMS

In 1985 the Federal Communications Committee (FCC) issued the Part 15 Rules which permitted unlicensed use and development of spread spectrum communications systems in the Industrial, Scientific, and Medical (ISM) band, consisting of three separate frequency ranges: 902-928 MHz, 2.4000-2.4835 GHz, and 5.725-5.850 GHz. The FCC raised the maximum transmit power for unlicensed systems in this band from less than one milliwatt for narrowband systems to up to one watt for spread spectrum systems based on their inherent ability to reject mutual interference. However, the following restrictions were placed on these unlicensed systems. [Ref. 5]

- For Frequency Hopping Spread Spectrum (FH/SS) systems

Maximum dwell time per hop:	400 msec
Minimum number of hop channels:	per Table 3.1

- For Direct Sequence Spread Spectrum (DS/SS) systems

Minimum spreading bandwidth:	500 kHz
Minimum processing gain:	10 dB

Subsequent to the FCC ruling, many spread spectrum products, including wireless networking devices, have been introduced to the consumer market. Initially, the communications systems used by these devices were proprietary in nature. However, to promote multi-vendor compatibility, the Institute of Electrical and Electronic Engineers (IEEE) has issued the IEEE 802.11 standard, governing the characteristics of wireless networking components. This standard will be discussed in Chapter IV.

Frequency Range	Maximum Channel Bandwidth	Minimum Number of Channels
902-928 MHz	500 kHz	50
2.4000-2.4835 GHz	1.0 MHz	75
5.725-5.850 GHz	1.0 MHz	75

Table 3.1: FCC Part 15 Rule Specifications for FH/SS Systems After Ref. [6]

For purposes of generality, the characteristics of generic frequency hopping and direct sequence systems will be discussed. Then, the constraints of the IEEE 802.11 standard will be applied and the advantages and disadvantages of each technique will be discussed.

A. FREQUENCY HOPPING SYSTEMS

A FH/SS communications system can be implemented by periodically varying the carrier frequency of a narrowband system. FH/SS systems can be categorized as either fast frequency hopping (FFH) or slow frequency hopping (SFH) depending upon the relationship between the period of the carrier frequency variation and the period of the transmitted symbol.

If the carrier frequency changes more rapidly than the transmitted symbol, the system is a FFH system. Each symbol is subsequently transmitted over multiple carrier frequencies with the signal between the carrier frequency hops referred to as a chip. If the difference in carrier frequencies exceeds the coherence bandwidth of the channel, each chip is received independently, providing a form of frequency diversity. If a chip is transmitted with a carrier frequency affected by a deep fade in the multipath channel, the receiver may still be able to reconstruct the symbol based upon the reception of the other independent chips. On the other hand, SFH systems provide no protection against deep fading. As the carrier frequency changes at a rate less than the symbol rate, many symbols are transmitted during each chip. As

a result, many symbols are lost when the carrier frequency lies in a deep fade region of the spectrum. Because many consumer products are designed to operate at symbol rates that exceed 10^6 symbols per second, FFH systems require costly frequency synthesizers to achieve hop rates greater than the symbol rates. At the expense of multipath channel performance, SFH systems use less expensive frequency synthesizers that vary the carrier frequency on the order of tens or hundreds of times vice millions of times per second. [Ref. 7]

Most FH/SS systems use a form of frequency shift keying (FSK) modulation. While phase shift keying (PSK) or differential PSK (DPSK) systems allow more efficient bandwidth utilization, the added requirement to maintain phase coherence during frequency hops proves prohibitive for inexpensive consumer applications. To provide an example of a FH/SS system, a binary FSK (BFSK) signal will be modulated by a frequency hopping modulator, as illustrated in Fig. 3.1.

The frequency of the FH modulator is selected from a discrete set of frequencies based upon the output of a pseudo-noise (PN) generator. The system could also be implemented by directly modulating the data signal with a BFSK modulator using a carrier frequency selected

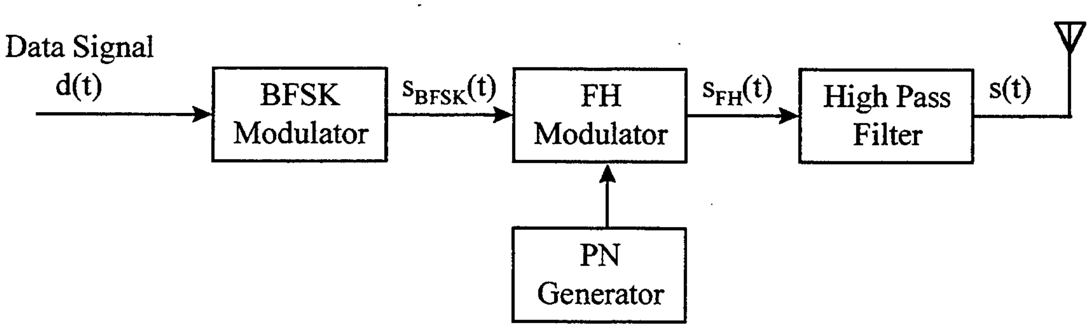


Figure 3.1: FH/SS System Using BFSK Modulation From Ref. [6]

from a discrete set by a PN generator, as is the case with most FFH systems; however, the resulting signal characteristics are the same. Let f_{FH} represent the frequency of the FH modulator. The BFSK signal can be represented as

$$s_{BFSK}(t) = A_c \cdot \cos\left[2\cdot\pi\cdot\left(f_c \pm \frac{\Delta f}{2}\right)\cdot t + \theta_0\right] \qquad [3.1]$$

where A_c represents the carrier signal amplitude, f_c the carrier frequency, and θ_0 the phase of the signal. The transmitted symbol is determined by the sign of the $\Delta f/2$ term. The output of the FH modulator can be expressed as

$$s_{FH}(t) = A_c \cdot \cos\left[2\cdot\pi\cdot\left(f_c \pm \frac{\Delta f}{2}\right)\cdot t + \theta_0\right]\cdot\left(2\cdot\cos\left(2\cdot\pi\cdot f_{FH}\cdot t\right)\right) \qquad [3.2]$$

$$\begin{aligned} s_{FH}(t) = A_c \Bigg\{ &\cos\left[2\cdot\pi\cdot\left(f_{FH} + f_c + \frac{\Delta f}{2}\right)\cdot t + \theta_0\right] \ldots \\ &+ \cos\left[2\cdot\pi\cdot\left[\left(f_{FH} - f_c\right) + \frac{\Delta f}{2}\right]\cdot t + \theta_0\right] \Bigg\} \end{aligned} \qquad [3.3]$$

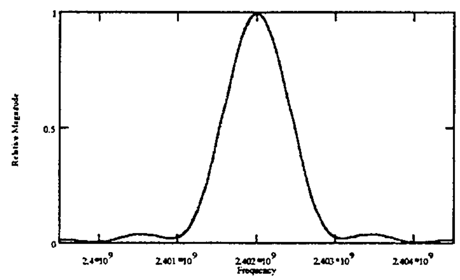
For proper signal reception, the PN generator at the transmitter and receiver must be synchronized. The high-pass filter, removing the low frequency components, provides the transmitted signal. [Ref. 7]

$$s(t) = A_c \cdot \cos\left[2\cdot\pi\cdot\left(f_{FH} + f_c \pm \frac{\Delta f}{2}\right)\cdot t + \theta_0\right] \qquad [3.4]$$

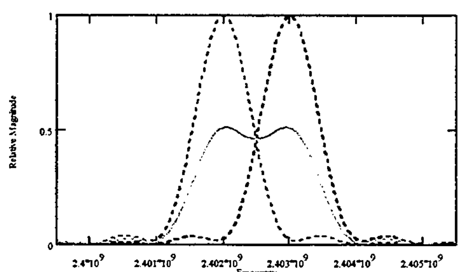
FH/SS systems that comply with the current IEEE 802.11 standard transmit at a data rate of either 1 Mbps or 2 Mbps. Two level Gaussian FSK (2GFSK) is used when transmitting

at 1 Mbps and four level Gaussian FSK (4GFSK) is used when transmitting at 2 Mbps. The carrier frequencies, consisting of (f_{FH} + f_c) from Eq. 3.4, range from 2.402 GHz to 2.48 GHz in steps of 1 MHz. [Ref. 8]

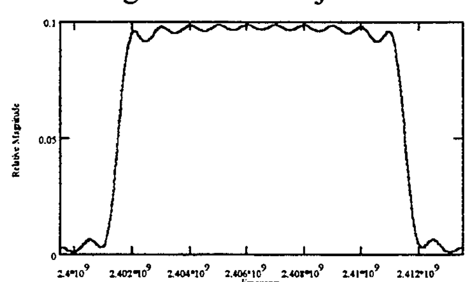
The instantaneous power spectral density (PSD) of the FH/SS signal consists simply of the PSD for the GFSK signal with a constant carrier frequency. This is shown in Fig. 3.2a for the 2FSK signal with a carrier frequency of 2.402 GHz. As the carrier frequency is hopped,



a. PSD of 2FSK Signal with 2.402 GHz Carrier Frequency



b. Time Averaged PSD for Adjacent FH/SS Chips



c. Time Averaged PSD for Ten Adjacent FH/SS Chips

Figure 3.2: Spectral Characteristics of FH/SS Signals

the PSD becomes the time average of the PSDs of the individual chips. This is illustrated in Fig. 3.2b for two 2FSK signals with carrier frequencies of 2.402 GHz and 2.403 GHz. Figure 3.2c shows the PSD generated by taking the time average of ten chips with carrier frequencies anging from 2.402 GHz to 2.411 GHz in steps of 1 MHz.

B. DIRECT SEQUENCE SYSTEMS

A DS/SS system is implemented by modulating a narrowband signal with a bipolar chipping code, c(t). The chipping code is generated by a PN generator and has a chip period given by the relationship

$$T_c = \frac{T_s}{k} \qquad [3.5]$$

where k is an integer describing the number of chips per symbol. Unlike FH/SS systems, DS/SS systems can utilize bandwidth efficient signals such as PSK or DPSK. A typical DS/SS system is shown in Fig. 3.3.

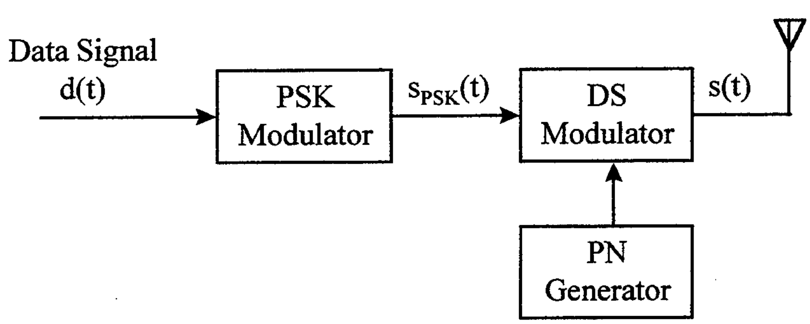


Figure 3.3: DS/SS System Using PSK Modulation From Ref. [6]

Given the bipolar data signal, d(t), the output of the PSK modulator for a binary PSK (BPSK) signal can be expressed as

$$s_{BPSK}(t)=d(t)\cdot A_c\cdot\cos\left(\omega_c\cdot t+\theta_0\right) \qquad [3.6]$$

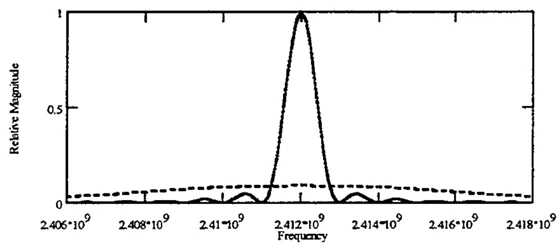
Modulating the signal with the chipping code generated by the PN generator yields the transmitted signal

$$s(t)=c(t)\cdot d(t)\cdot A_c\cdot\cos\left(\omega_c\cdot t+\theta_0\right) \qquad [3.7]$$

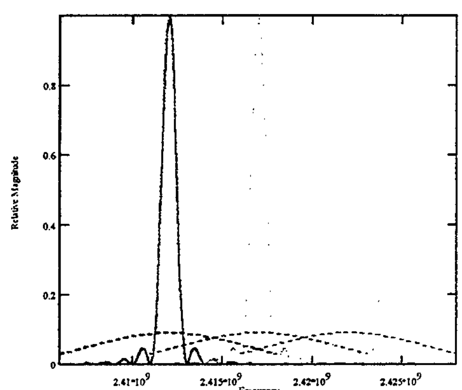
At the receiver, the DS modulation is removed by again applying the chipping code modulation. Those chips initially modulated by c(t) = -1 are again multiplied by c(t) = -1, producing the original signal. Obviously, for a successful DS/SS system, the PN generator at the transmitter and receiver must be synchronized. [Ref. 7]

Currently, DS/SS systems that are IEEE 802.11 compliant transmit at a rate of 1 Mbps or 2 Mbps in the 2.4 GHz range of the ISM band. The higher data rate utilizes quadrature DPSK (QDPSK) modulation while the lower rate uses binary DPSK (BDPSK) modulation. In the United States the carrier frequency ranges from 2.412 GHz to 2.462 GHz depending upon which of the eleven channels is selected. Each channel is separated by 5 MHz. An 11-bit Barker sequence is used for the chipping code with the spectrum spreading effects for a signal using a 2.412 GHz carrier frequency shown in Fig. 3.4a. [Ref. 8] Applying the chipping code to the PSK signal effectively produces a new PSK signal with a symbol duration of T_c instead of T_s. Thus, the chipping code spreads the spectrum by a factor of k. [Ref. 7]

Figure 3.4b shows the spreading effects on signals using adjacent channels. It is apparent that adjacent channels suffer from mutual interference. While the interference rejection characteristics of DS/SS systems help to mitigate the effects of the interference, it is recommended that channels used in the same physical area be separated by at least 30 MHz. Figure 3.5 shows that the mutual interference is nearly negligible with 25 MHz channel separation using carrier frequencies of 2.412 GHz, 2.437 GHz, and 2.462 GHz.



a. PSD for DS/SS System Using 11-bit Chipping Code
with 2.412 GHz Carrier Frequency



b. PSDs for Adjacent Channels of DS/SS System Using 11-bit
Chipping Code with 5 MHz Separation

Figure 3.4: Spectral Characteristics of DS/SS Signals

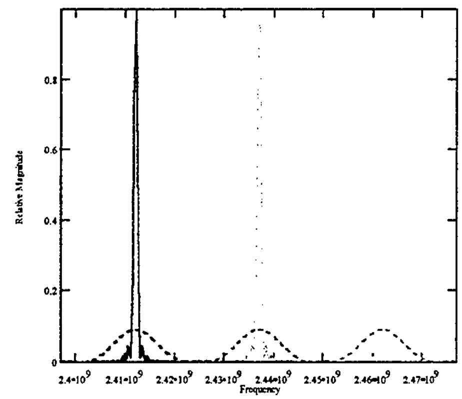


Figure 3.5: PSDs of DS/SS Channels Using 11-bit Chipping Code with 25 MHz Separation

From examining the effects of direct sequence spreading on spectral representations, it is apparent that DS/SS systems are inherently resistant to the effects of deep fade regions in multipath channels. The deep fade regions may cause the loss of one or two chips of a transmitted signal, but the unaffected chips will recombine during spectrum despreading to form a weakened, but detectable, PSK signal.

An additional advantage to using DS/SS modulation is the ability to utilize RAKE receivers. As explained in Chapter II, the shipboard channel provides multipath propagation in which multiple reflections of the transmitted signal are received with different propagation delays. RAKE receivers apply staggered time delays to account for varying propagation paths and allow signal combination to effectively increase the received energy of the signal. Thus, RAKE receivers serve to combine separate multipath receptions.

C. FREQUENCY HOPPING VS. DIRECT SEQUENCE

As described above, FH/SS and DS/SS systems are fundamentally different. The major theoretical differences that could effect performance can be categorized into three topics: Interference Resistance, Scalability, and Room for Growth. The actual performance of representative FH/SS and DS/SS components is evaluated in detail in Chapter V.

1. Interference Resistance

As explained above, the means by which FH/SS and DS/SS systems combat interference, specifically the narrowband interference created by deep fade regions, is different. Most FH/SS systems, including all IEEE 802.11 compliant devices, are implemented using SFH modulation. Instead of providing protection against deep fade regions of the multipath environment, these FH/SS systems rely on the probability that most of their transmitted frequencies will occupy flat-fading regions of the channel spectrum. The symbols that are transmitted in deep fade channels will be retransmitted after the carrier hops to an unaffected frequency. On the other hand, the DS/SS signal is spread so that the demodulated received signal will be virtually unaffected by deep fade regions of the multipath environment. This increase in interference resistance is gained through the sacrifice of bandwidth efficiency.

2. Scalability

Scalability refers to the ability to physically collocate multiple FH/SS or DS/SS systems without generating unbearable mutual interference. As illustrated in Fig. 3.2b and Fig. 3.4b, the presence of mutual interference renders adjacent channels unusable. For DS/SS, Fig. 3.5 shows that while 30 MHz of channel separation is recommended, acceptable performance is

achieved with three collocated channels operating with 25 MHz of separation. Thus, no more than three collocated DS/SS systems are feasible for the 2.4 GHz frequency portion of the ISM band. FH/SS systems offer a more efficient use of the allocated bandwidth. While the IEEE 802.11 standard calls for 79 channels, the mutual interference becomes unacceptable if more than fifteen channels are collocated. While it seems safe to assume that the aggregate throughput of the fifteen collocated FH/SS systems would exceed that of three collocated DS/SS systems, that is not necessarily the case. It has been reported that FH/SS aggregate performance peaks with thirteen collocated IEEE 802.11 compliant systems offering less total throughput than three collocated IEEE 802.11 compliant DS/SS systems [Ref. 9]. In fact, the User's Manual for an IEEE 802.11 compliant, FH/SS wireless networking card reports a maximum aggregate throughput of only 5 Mbps [Ref. 10]. Additionally, due to the inherent robustness of the DS/SS signal, direct sequence systems using the same channel can be placed closer together than frequency hopping systems [Ref. 11].

3. Room for Growth

FH/SS systems are severely limited by the utilization of FSK modulation. The 1 MHz channel bandwidth required by the FCC Part 15 rules allows only BFSK or QFSK modulation. The data rate gain achieved by increasing the number of bits per symbol is restricted by compliance with the maximum channel bandwidth limitation. DS/SS systems utilize the more bandwidth efficient PSK modulation where the bandwidth does not increase with signal complexity. Thus, greater data rates can be achieved by utilizing more bits per symbol at the expense of an increase in transmit power or a decrease in range [Ref. 11].

THIS PAGE INTENTIONALLY BLANK

IV. WIRELESS NETWORKING AND THE IEEE 802.11 STANDARD

Developing components that enable diverse computing systems to communicate and share data is a monumental achievement. Communication signals must be tailored for transmission over a specified medium. Protocols must be developed and implemented for managing data transfer. Ultimately, each computer system involved must be capable of correctly transmitting, receiving, interpreting, and utilizing the data.

To aid in developing networking systems, the International Standards Organization developed the Open System Interconnection (OSI) model illustrated in Fig. 4.1. The OSI model divided required functionality into seven abstract layers. Components could then be designed with the functionality of specific layers of the OSI model and, combined with other devices, could enable diverse computing systems to interoperate. Figure 4.1 also shows that

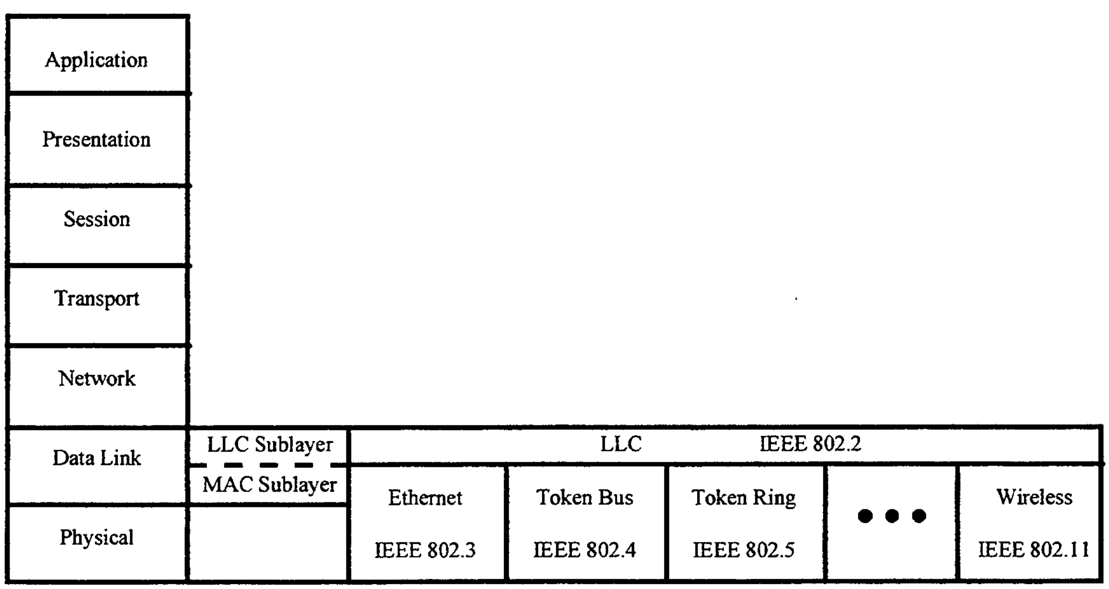
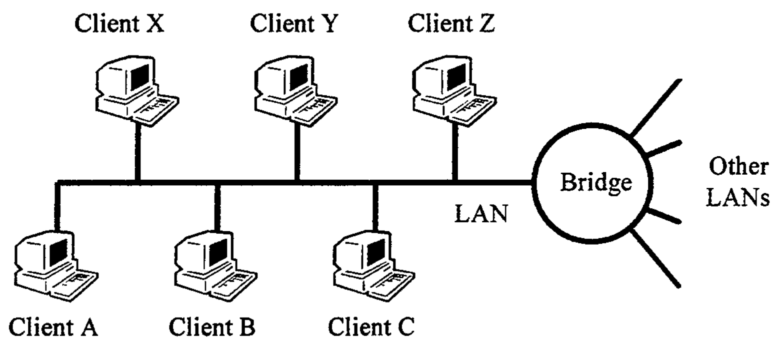


Figure 4.1: The OSI Model After Ref. [1]

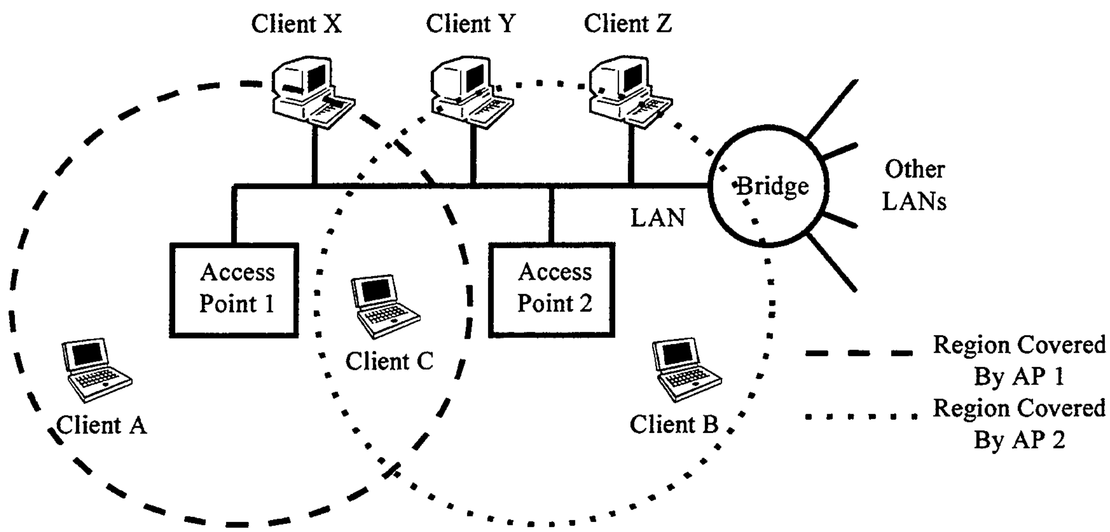
attempts to detect and correct or discard errors in received data. The flow control aspects of the LLC sublayer controls the transmission and acknowledgment of data frames. [Ref. 12]

Simply replacing the physical layer aspects of networking components with radio transmitters will not produce a wireless network. Figure 4.2a shows a topographical diagram of a typical bus oriented LAN. Each client is connected to the network by a physical link, typically twisted pair, coaxial cable, or optical fiber. Figure 4.2b shows a similar network utilizing both wired and wireless connections. Clients X, Y, and Z are still physically connected to the network bus but clients A, B, and C are connected to the network through radio frequency links with access points (APs). These APs pass data packets between their wireless clients and the guided distribution component of the network. Figure 4.2c shows a topography referred to as an ad-hoc wireless network. The clients of ad-hoc networks communicate only between themselves and are not connected with guided media. Each of the topographies shown in Fig. 4.2 differs only slightly in physical layout, but there are significant differences in how the clients of the network interoperate. In Fig. 4.2b it is clear that clients A and B communicate with the network through their respective APs. However, client C could be associated with either AP 1 or AP 2. Simply transmitting data to both APs would produce duplicated data on the network, degrading efficiency. Additionally, the wireless network shown in Fig. 4.2b must allow dynamic association between mobile clients and the APs. As a mobile client roams from an area covered by one AP to another, the transition must appear seamless to the upper layers of the OSI model.

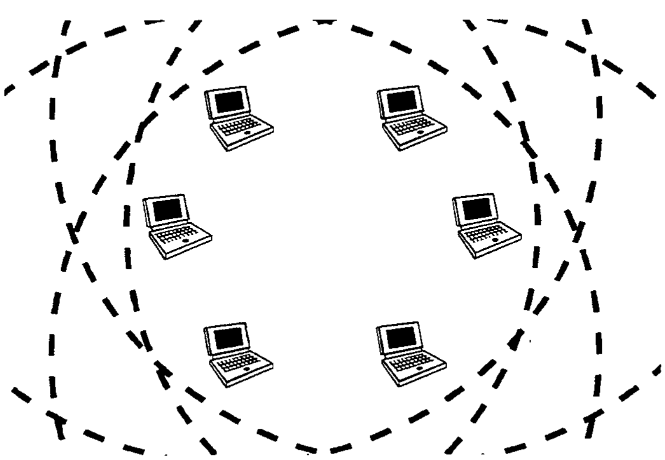
As shown in Fig. 4.1, specific network architectures are implemented in the lowest two layers of the OSI model. In fact, the architecture is determined by the physical layer and the



a. Conventional LAN



b. Infrastructure-Based WLAN



c. Ad-hoc WLAN

Figure 4.2: LAN Configurations

MAC sublayer. Common network architectures share the same LLC sublayer protocol described in the IEEE 802.2 standard. To examine the significant differences between conventional LANs and WLANs, two IEEE 802 standards will be examined. First the physical layer and the MAC sublayer characteristics of common Ethernet LANs, governed by the IEEE 802.3 standard, will be discussed. Finally, the physical layer and the MAC sublayer of the IEEE 802.11 standard for WLANs will be described.

A. THE IEEE 802.3 STANDARD: CSMA/CD NETWORKS

Ethernet LANs continue to be popular for most network installations. These networks are relatively easy to install and maintain. While Ethernet is commonly used interchangeably with CSMA/CD or IEEE 802.3 LANs there are some slight differences. Therefore, the CSMA/CD network characteristics will be described, but these characteristics can be generally applied to networks commonly referred to as Ethernet LANs. [Ref. 12]

1. The Physical Layer

As shown in Table 4.1, the IEEE 802.3 standard specifies several physical media and signaling techniques. These implementation options provide flexibility for the network designers. The most common form of the IEEE 802.3 LAN utilizes the 10BASE-T format. Although broadband signaling is permitted with 10BROAD36 implementations, most CSMA/CD LANs use baseband signaling with Manchester coding.

	10BASE5	10BASE2	10BASE-T	10BROAD36	10BASE-FP
Transmission Medium	Coaxial Cable	Coaxial Cable	Unshielded Twisted Pair	Coaxial Cable	Optical Fiber
Signaling Technique	Baseband (Manchester)	Baseband (Manchester)	Baseband (Manchester)	Broadband (DPSK)	OOK (Manchester)
Network Topology	Bus	Bus	Star	Bus/Tree	Star

Table 4.1: Description of IEEE 802.3 Physical Media After Ref. [1]

2. The MAC Sublayer

For IEEE 802.3 LANs medium access is governed by a CSMA/CD protocol. When a network client has data to transmit, it first attempts to determine if the channel is idle. If no transmissions are detected, the client will begin to transmit its data packet. If the medium is not idle, the client will wait until the channel is clear and then begin transmission. Keeping in mind that transmitted signals propagate at a finite speed dependent upon the transmission media, it is clear that this MAC protocol does not prevent data collisions. One network client could determine that the channel is idle and begin to transmit data. During the time required for signal propagation, another client could sense that the channel is idle and also begin to transmit data. A data collision or an overlapping of transmitted signals would occur. [Ref. 1]

How a data collision is detected depends upon the specific implementation of the CSMA/CD network. In baseband, bus topology networks, a collision is detected when the amplitude of the signal exceeds the maximum permitted value. For broadband implementations, where a client's transmitting and receiving connections are separated by a finite distance, collisions are detected by a bit-by-bit comparison of the sensed signal and the transmitted signal [Ref. 1]. Collision detection for star topology networks can be implemented

in the design of the network hubs. Anytime more than one branch of a hub is transmitting, a collision will occur.

When a transmitting client detects a data collision, it transmits a short jamming signal to ensure that all clients are aware of the collision [Ref. 1]. The clients affected by the data collision then enter a random backoff period prior to attempting to retransmit to minimize the probability of reoccurring collisions. The IEEE 802.3 standard specifies the use of a binary exponential backoff algorithm. After the initial collision occurs, the affected clients wait either zero or one time interval. If a second collision occurs then the clients will randomly wait zero, one, two, or three time intervals. The maximum time delay continues to double on reoccurring collisions until the tenth collision. For collisions occurring after the tenth, the maximum time delay stays constant.

B. THE IEEE 802.11 STANDARD: WIRELESS NETWORKS

While industries continue to leverage information systems to increase efficiency, computer applications are developed to assist personnel in the performance of tasks in the workspace. As not all workspaces are defined by cubical walls, comfortable chairs, and deskspace suitable for desktop or laptop computers, many portable computing devices have been developed. The need to connect these portable computers to LANs has driven the production of wireless networking solutions. Just as the IEEE 802 standards have enabled multivendor compatibility for conventional LAN architectures, the IEEE 802.11 standard strives to do the same for WLANs. As illustrated in Fig. 4.2b and Fig. 4.2c, there are two basic categories of WLANs. Only the infrastructure base architecture shown in Fig. 4.2b will

be discussed. Ad-hoc networks can be viewed as inexpensive, low impact implementations of small computer network; however, the purpose of most WLANs is to enable information sharing between wireless, portable clients and clients connected to an existing conventional network. Additionally, because this project deals with enabling mobile applications onboard naval vessels, including the relaying of DC information, only the infrastructure-based architecture of Fig. 4.2b is prudent.

1. The Physical Layer

The IEEE 802.11 standard specifies three physical implementations: one infrared standard and two radio frequency standards. The infrared communication channel requires a direct line of sight between network clients and is considered impractical for the purposes of this study. The radio frequency implementations utilize either DS/SS or FH/SS communication systems in the 2.4 GHz region of the ISM band. The DS/SS and FH/SS systems specified in the IEEE 802.11 standard are discussed in more detail in Chapter III.

2. The MAC Sublayer

The MAC sublayer handles medium access in both a contention and a contention-free mode. The contention mode utilizes an adaptation of the CSMA/CD protocol called carrier-sense multiple access with collision avoidance (CSMA/CA) and is implemented in the Distributed Coordination Function (DCF) sublayer of the MAC Sublayer. Collision detection is not feasible because all of the clients contending for medium access may not be able to detect signals transmitted by distant or hidden clients. Prior to transmitting data packets, a client senses the channel to attempt to determine if another client is transmitting. If the channel is

clear, the client will then wait an interframe space (IFS) interval whose length is based upon the nature of the data packet being transmitted. If the channel remains clear during the IFS then the client can transmit the data packet. If the medium was initially busy or a transmission was detected during the IFS then the client must wait. Once the channel becomes clear, the client automatically enters a random backoff period similar to the binary exponential backoff used in the CSMA/CD algorithm. This backoff period is used even though no collisions have occurred. This automatic backoff reduces collisions that frequently occur following the completion of the transmission of a data packet. [Ref. 1]

Additionally, the DCF sublayer provides a means for medium reservation. To improve the network performance in the presence of hidden clients, a Request to Send/Clear to Send (RTS/CTS) protocol may be used. A client with data to transmit initially sends a short RTS signal. All clients that receive the RTS signal will not attempt to transmit until either a CTS signal is received or a finite time limit expires. The destination client, once it has received a RTS signal, will respond with a CTS signal if it is ready to receive the transmission. The CTS signal will contain a duration during which no clients other than the requesting client will attempt to transmit data. [Ref. 7]

The MAC sublayer also includes a contention-free mode, which is implemented in the Point Coordination Function (PCF) sublayer. The PCF sublayer permits channel access through the use of a polling station, an AP that allows its clients to transmit in a round-robin fashion. WLANs can operate in either a contention mode or an alternating contention/contention-free mode.

As mentioned above, wireless networks do not use collision detection. Clients associated with an AP need only communicate with that AP, not with all the other clients associated with that AP. Thus, it is possible that one client may not be able to detect another client's transmissions. If a client is unable to detect transmissions, it is also unable to detect collisions. Because collisions are not detected, lost data packets occur more frequently in WLANs than in conventional LANs. To mitigate the effects of the lost packets, the MAC sublayers incorporate an acknowledgment feature. These acknowledgment frames serve to inform the sending station that the transmitted frame was received. If an acknowledgment is not received within a certain time period, the data packet is assumed lost and is retransmitted by the sending station. [Ref. 1]

The other added feature offered by MAC sublayers of WLANs is the provision for roaming. Wireless clients associate and disassociate with APs as necessary to maintain connection with the wired portion of the network. The APs periodically transmit beacon signals to allow clients to determine the appropriate AP with which to associate. While a client can be associated with at most one AP, it is possible for clients to roam outside of coverage areas and become disconnected from the network. Data transfers from a wireless client to the network are passed to the associated AP. Likewise, the APs receive data for associated clients from the wired portion of the network and then transmit them over the wireless medium. Uncontrolled association to multiple APs would create duplicated data packets over both the wired and wireless media.

V. LABORATORY TESTING

Laboratory testing was conducted on the second floor of Bullard Hall at the Naval Postgraduate School (NPS) in Monterey, California. The purpose of the testing was to comparatively evaluate four commercially available wireless networking components. Two of the components utilized DS/SS techniques, only one of which was IEEE 802.11 compliant. Likewise, the other two consisted of a FH/SS, IEEE 802.11 compliant component and one that was non-compliant. The components tested are listed in Table 5.1. The goal of the testing was to evaluate the four dissimilar components in a multipath environment. As all components were dissimilar, no interoperability between vendors existed. Because the laboratory will not have the same characteristics as a shipboard compartment, the results of the testing merely provide a gauge to compare the performance of the components in a controlled environment, not an accurate measure of expected range or throughput in the field.

As the testing focused on the performance of the wireless components, efforts were made to mitigate the contributions of other factors in the measured performance. For example, the testing was conducted using the same computer equipment. Therefore, performance gains due to computer microprocessor differences or operating system efficiencies will not taint the

Categories	Frequency Hopping	Direct Sequence
IEEE 802.11 Non-Compliant	Proxim RangeLAN2	Lucent Technologies WaveLAN
IEEE 802.11 Compliant	Breezecom BreezeNET Pro.11	Lucent Technologies WaveLAN IEEE

Table 5.1: Wireless Components

results.

The remainder of this chapter involves the radio frequency component evaluation. First, the testing procedures are discussed. Then, each wireless component is described and the individual testing results are discussed. Finally, the testing results are comparatively analyzed.

A. TEST EQUIPMENT AND PROCEDURES

Four laboratory tests were used to evaluate the wireless networking components. First, the range of coverage in the multipath environment provided by the laboratory was determined. Next the throughput was measured at varying levels of signal strength using a single wireless client and AP. The throughput measurement was then repeated using two wireless clients and a single AP. Finally, a single client was used with two APs to verify roaming capabilities.

1. Test Equipment

For consistency of results, the same computer equipment was used for testing each of the wireless components. During the throughput testing, it was noted that different wireless clients produced different results; however, the performance of all wireless components were similarly effected. Thus, the differences in performance were attributed to the differences between the wireless clients in question. To enable the testing to be accurately reproduced, each of the devices used is described below. Figure 5.1 illustrates a typical test configuration.

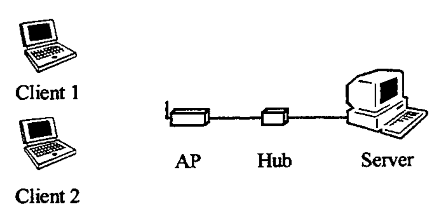


Figure 5.1: Typical Test Configuration

- **Server:** A Dell Dimension XPS R400 desktop computer with the following characteristics was used as the network server.
  - Pentium II processor operating at 400 MHz
  - 128 MB random access memory (RAM)
  - Windows NT (version 4.0) operating system
- **Hub:** A 10Mbps Kingston EtherRX Soho hub was used to connect the server with the AP using 10BaseT cabling.
- **AP:** The AP was selected based upon which wireless component was tested.
- **Client:** Two wireless clients were used for the testing. These computers were selected as representatives of portable devices suitable for use in a shipboard environment. While laptops would have proven easier to use for the purposes of the test, it is not practical to assume that a laptop is a feasible choice as a portable device for shipboard use.
  - **ViA II Flex:** The Flex is a fanny-pack wearable computer with a hip-holstered tablet display and interface. It contains a 180 MHz Cyrix processor and 64 MB RAM and uses Windows 98 as the operating system. This device was used for all single client throughput tests. The Flex is shown in Fig. 5.2 below.
  - **Mitsubishi Amity:** The Amity is a pen-based tablet computer measuring 10 inches long by 6.7 inches wide and 1.3 inches thick. It contains an AMD 5x86 processor operating at 133 MHz with 32 MB RAM and uses Windows 95 as

the operating system. The Amity was used when required for two client throughput measurement. It is shown in Fig. 5.3.

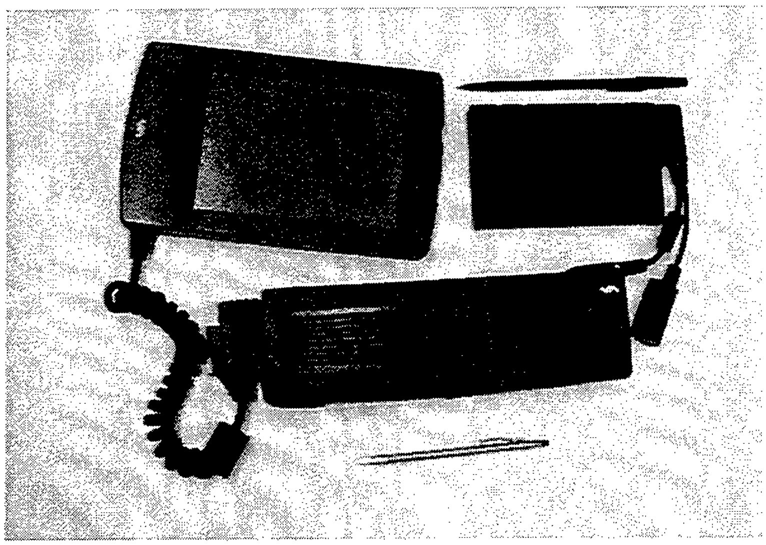


Figure 5.2 ViA II Flex Wearable Computer

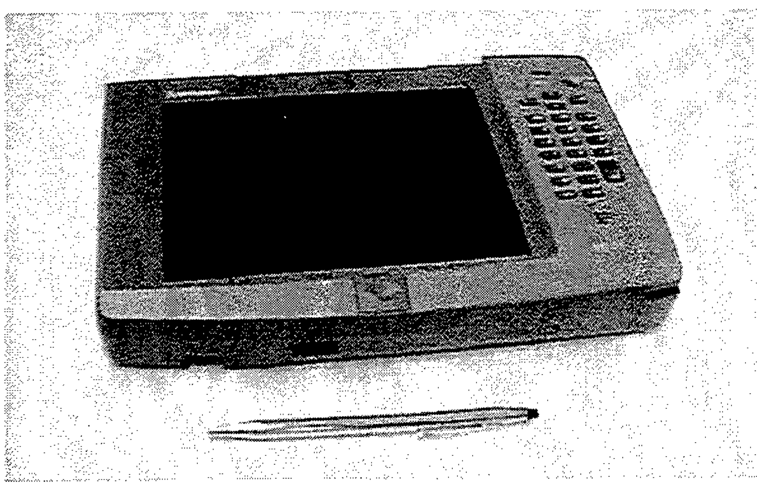


Figure 5.3: Mitsubishi Amity Tablet Computer

2. Test Procedures

a) Coverage Determination

Each wireless component included a proprietary diagnostic tool to assist in performance evaluation. The data provided varied in nature from a percentage signal strength to a measured signal to noise ratio. While direct comparison of the proprietary metrics yields little, these diagnostic tools provide two useful functions. First, a maximum range of coverage can be easily determined. Second, these signal strengths provide regional boundaries for the measurement of throughput in the following tests.

For the coverage determination, the position of the wireless client was slowly varied and the signal strength recorded. The maximum range was found to be the point at which the client was no longer able to maintain communications with the AP.

b) Single Client Throughput Determination

Using the results of the coverage test, the entire coverage area was subdivided into ranges of signal strength. Within these ranges, single client throughput was measured using a large file transfer. A 5 MB file was transferred from the client to the server and vice-versa using a file transfer protocol (FTP) program. The file size was selected to provide a long enough transfer duration for statistical accuracy without the file becoming too cumbersome. The FTP program provided a throughput calculation based upon the file size and required transfer time.

c) *Multiple Client Throughput Determination*

The throughput testing was repeated using two wireless clients simultaneously conducting file transfers. The purpose of using two clients was to determine the ability of the AP to efficiently manage multiple clients.

d) *Roaming Verification*

Two APs were used to verify that the wireless components could seamlessly roam during data transfer. When associated with the first AP, the wireless client commenced a file transfer. The client was then moved to where it disassociated with the first AP and associated with the second. The roaming was considered successful if the file transfer was completed successfully regardless of the shift in association. All wireless components evaluated were able to successfully roam between APs.

B. WIRELESS NETWORKING COMPONENTS AND TEST RESULTS

As shown in Table 5.1, four dissimilar wireless components were evaluated. The description of the components and the results of the tests are given below.

1. Proxim RangeLAN 2 Components

Prior to the release of the IEEE 802.11 standard, Proxim held the majority of the commercial market share for wireless networking equipment. This lead in market share can be attributed to an early time to market and the low cost due to the relatively inexpensive components required by SFH systems. Figure 5.4 shows the Proxim components evaluated in

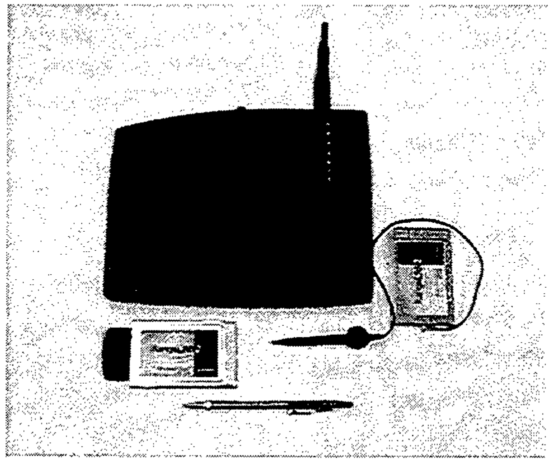


Figure 5.4: Proxim RangeLAN2 Components

testing: the RangeLAN2 Ethernet AP tranceiver and the RangeLAN2 PCMCIA wireless network adapter cards. The characteristics of these components are provided below. [Ref. 13]

• **Type:**	FH/SS, IEEE 802.11 Non-Compliant	
• **Advertised Range:**	Indoors	400 ft
	Outdoors	700 ft
• **Maximum Data Rate:**	1.6 Mbps in high signal strength	
	800 kbps in low signal strength	
• **PC Card Transmit Power:**	100 mW	
• **Consumed Power:**	Transmit	300 mA
	Receive	150 mA
	Sleep	2-5 mA

a) Coverage

Figure 5.5 shows an overlay of the range of coverage offered by the RangeLAN2 AP. The proprietary diagnostic tool offered by Proxim provides signal strength

as measured in percentage. Subdivisions of the coverage area were created based upon the measured signal strength. These subdivisions are shown in Fig. 5.5 and are used in the throughput tests.

b) Single Client Throughput

Table 5.2 shows the results of the single client throughput testing conducted at various locations throughout the subdivisions of the coverage area. Even considering the data overhead involved, the results are far from what should be expected of a component with a maximum instantaneous data rate of 1.6 Mbps.

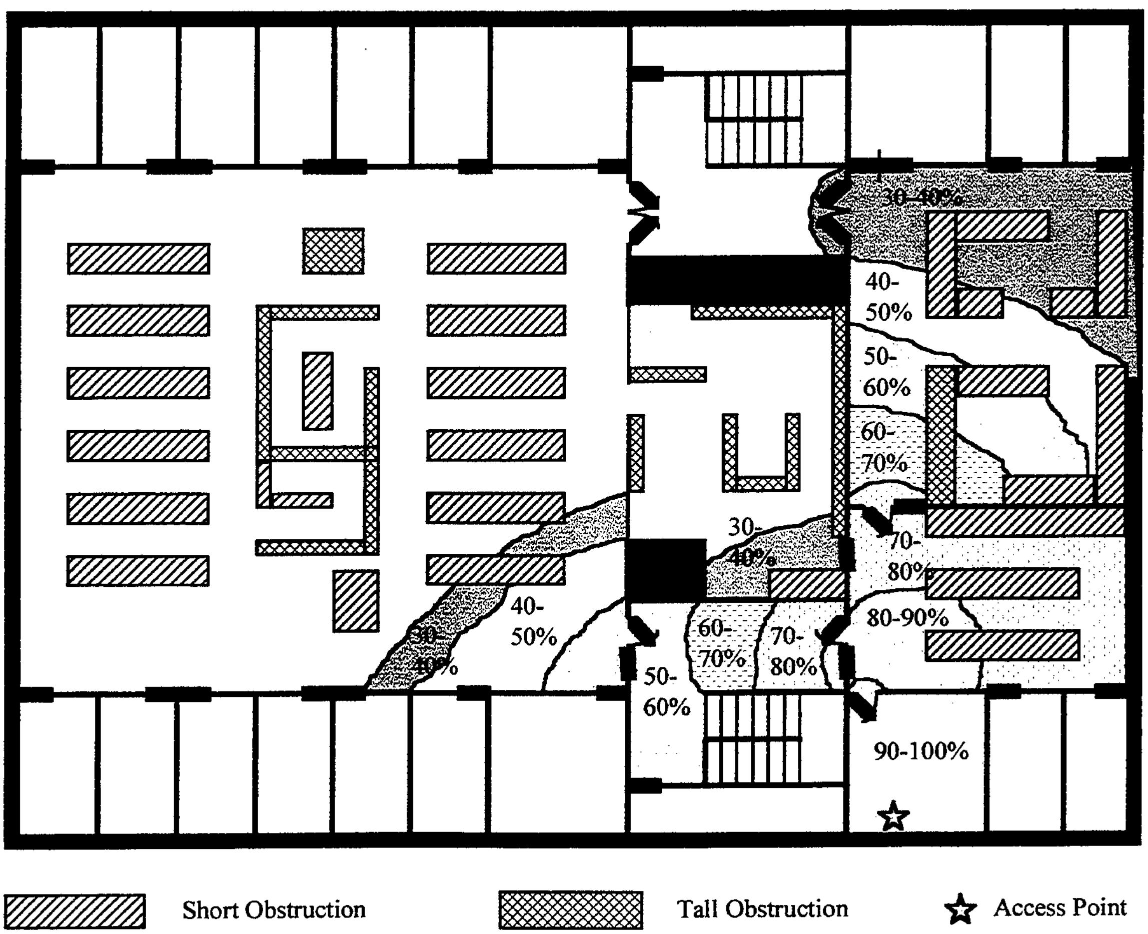


Figure 5.5: Proxim RangeLAN2 Coverage

Iteration	Direction	Percentage Signal Strength						
		90-100	80-90	70-80	60-70	50-60	40-50	30-40
1	Client to Server	415	452	458	443	441	399	277
	Server to Client	596	395	549	338	338	365	270
2	Client to Server	448	430	453	324	295	350	305
	Server to Client	441	347	410	337	321	392	259
3	Client to Server	459	457	337	360	383	378	283
	Server to Client	557	553	385	272	365	330	218
4	Client to Server	447	416	423	375	411	341	294
	Server to Client	578	371	333	356	368	297	260
5	Client to Server	429	446	417	362	412	362	278
	Server to Client	370	507	361	340	355	340	308
Average Throughput		474	437.4	412.6	350.7	368.9	355.4	275.2

Table 5.2: Proxim RangeLAN2 Single Client Throughput Measurements (in kbps)

c) *Multiple Client Throughput*

Table 5.3 shows the results of the throughput measurements conducted with two clients performing simultaneous file transfers.

Iteration		Direction	Percentage Signal Strength						
			90-100	80-90	70-80	60-70	50-60	40-50	30-40
1	Client 1	Client to Server	186	190	170	199	161	131	134
		Server to Client	321	305	295	286	260	202	121
	Client 2	Client to Server	191	185	174	188	173	167	98
		Server to Client	327	315	303	296	280	225	125
2	Client 1	Client to Server	194	188	177	185	162	134	102
		Server to Client	331	339	315	320	267	203	205
	Client 2	Client to Server	199	196	190	179	171	149	113
		Server to Client	349	369	327	320	250	231	219
3	Client 1	Client to Server	195	194	180	184	156	139	135
		Server to Client	335	291	329	315	241	204	211
	Client 2	Client to Server	200	199	185	193	170	161	166
		Server to Client	351	321	325	322	270	231	231
4	Client 1	Client to Server	186	188	180	182	154	169	81
		Server to Client	330	326	301	282	245	215	120
	Client 2	Client to Server	187	192	199	186	170	159	129
		Server to Client	343	328	318	301	267	232	141
Average Throughput			264.0625	257.875	248	246.125	212.3125	184.5	145.6875

Table 5.3: Proxim RangeLAN2 Multiple Client Throughput Measurements (in kbps)

d) Roaming Verification

The RangeLAN2 components successfully completed the roaming test.

2. BreezeCOM BreezeNET Pro.11 Components

BreezeCOM offers the BreezeNET Pro.11 line as FH/SS, IEEE 802.11 compliant WLAN components. The AP and PCMCIA card are shown in Fig. 5.6. In addition to being IEEE 802.11 compliant at the 1 Mbps and 2 Mbps data rates, the BreezeNET Pro.11 offers a faster, non-compliant data rate. When in the presence of non-BreezeNET components, the devices will limit their data rates to those compliant with the IEEE standard; however, they will utilize the faster data rate when sufficient signal strength exists in networks consisting solely of BreezeNET components. The characteristics of the components are provided below. [Ref. 9]

- **Type:** FH/SS, IEEE 802.11 Compliant
- **Advertised Range:**

Open Office	600 ft
Semi-Open Office	300 ft
Closed Office	150 ft

Actual range dependent upon environment.

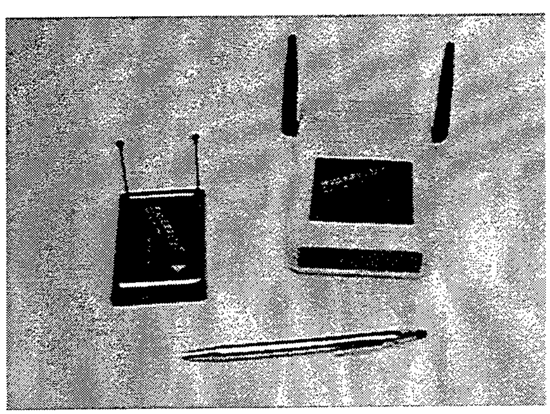


Figure 5.6: BreezeCOM BreezeNET Pro.11 Components

- **Maximum Data Rate:** 3 Mbps in exceptional signal strength
  2 Mbps in high signal strength
  1 Mbps in low signal strength
- **PC Card Transmit Power:** 100 mW
- **Consumed Power:**

	Transmit	360 mA
	Receive	285 mA
	Sleep	< 30 mA

a) Coverage

Figure 5.7 shows an overlay of the coverage area provided by the BreezeNET components. While the advertised ranges advise that actual range is dependent upon the environment, the coverage area was determined to be much smaller than expected.

b) Single Client Throughput

Table 5.4 shows the results of the throughput testing conducted at various locations in the subdivisions of coverage shown in Fig. 5.7. While the BreezeNET components offer good throughput in regions of high signal strength, the performance falls short of what is expected for components rated at 3 Mbps. Additionally, as signal strength degrades, the throughput falls rapidly.

c) Multiple Client Throughput

Table 5.5 shows the results of the throughput measurements conducted with two clients performing simultaneous file transfers.

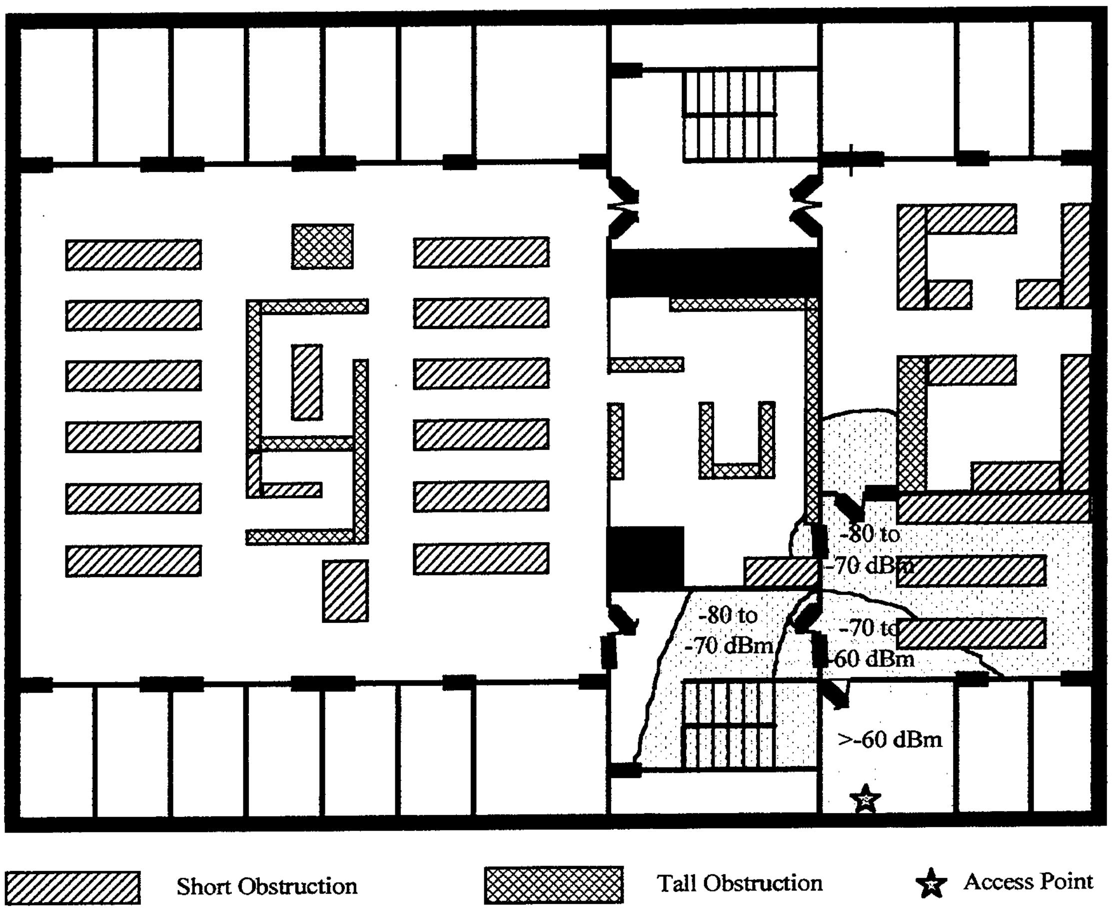


Figure 5.7: BreezeCOM BreezeNET Pro.11 Coverage

Iteration	Direction	Signal Strength (dBm)		
		> -60	-60 to -70	-70 to -80
1	Client to Server	1040	610	364
	Server to Client	1530	654	445
2	Client to Server	1050	636	350
	Server to Client	1370	828	484
3	Client to Server	1040	543	412
	Server to Client	1620	829	538
4	Client to Server	1010	742	158
	Server to Client	1020	741	197
5	Client to Server	1060	894	312
	Server to Client	1150	1020	423
Average Throughput		1189	749.7	368.3

Table 5.4: BreezeCOM BreezeNET Pro.11 Single Client Throughput Measurements (in kbps)

Iteration		Direction	Signal Strength (dBm)		
			> -60	-60 to -70	-70 to -80
1	Client 1	Client to Server	630	556	246
		Server to Client	820	523	322
	Client 2	Client to Server	753	573	263
		Server to Client	801	519	323
2	Client 1	Client to Server	625	487	248
		Server to Client	824	486	283
	Client 2	Client to Server	701	579	244
		Server to Client	837	499	281
3	Client 1	Client to Server	665	488	256
		Server to Client	762	504	277
	Client 2	Client to Server	712	559	240
		Server to Client	803	517	292
4	Client 1	Client to Server	649	522	246
		Server to Client	816	543	268
	Client 2	Client to Server	714	572	234
		Server to Client	833	574	288
Average Throughput			746.5625	531.3125	269.4375

Table 5.5: BreezeCOM BreezeNET Pro.11 Multiple Client
Throughput Measurements (in kbps)

d) Roaming Verification

The BreezeNET components successfully completed the roaming test.

3. Lucent Technologies WaveLAN Components

The Lucent Technologies WaveLAN components were chosen to represent the DS/SS, IEEE 802.11 non-compliant products. These products, however, are no longer commercially available. Current Lucent Technologies products are IEEE 802.11 compliant at the 1 Mbps and 2 Mbps and offer faster performance at data rates that are not compliant with the standard. These components are still evaluated to compare the relative performance of IEEE 802.11 compliant and non-compliant devices at the 2 Mbps data rate.

One advantage offered by the Lucent Technologies product is that the AP can be used with either the compliant or the non-compliant devices. The AP actually has two PCMCIA slots and uses PCMCIA wireless network adapter cards much like the clients. It is actually possible to bridge between compliant and non-compliant WLANs using one of each PCMCIA cards in the two slots. The Lucent Technologies WavePOINT-II AP and the WaveLAN PCMCIA cards are shown in Fig. 5.8.

The characteristics of the WaveLAN components are given below. It is important to note that these devices only operate at the 2 Mbps data rate. Thus, these components cannot use the increased symbol energy provided through slowing the symbol rate. [Ref. 14]

- **Type:** DS/SS, IEEE 802.11 Non-Compliant
- **Advertised Range:**

Open Office	600 ft
Semi-Open Office	160 ft
Closed Office	80 ft

Actual range dependent upon environment.

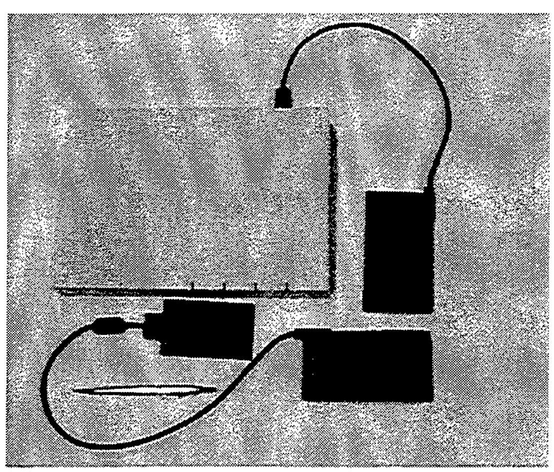


Figure 5.8: Lucent Technologies WaveLAN Components

- **Maximum Data Rate:** 2 Mbps
- **PC Card Transmit Power:** 32 mW
- **Consumed Power:**

Transmit	365 mA
Receive	315 mA
Sleep	35 mA

a) Coverage

Figure 5.9 shows an overlay of the coverage area provided by the WaveLAN components.

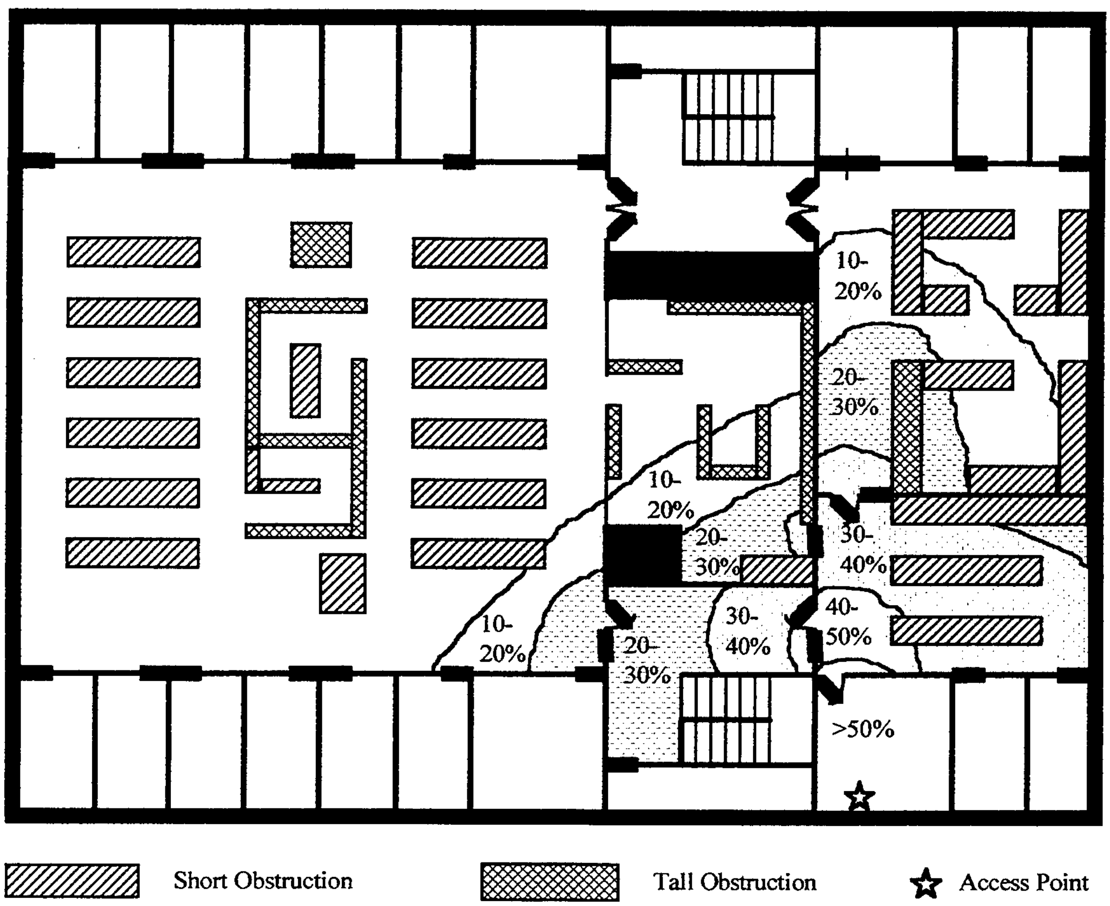


Figure 5.9: Lucent Technologies WaveLAN Coverage

b) Single Client Throughput

Table 5.6 shows the results of the throughput testing conducted at various locations in the subdivisions of coverage shown in Fig. 5.9.

c) Multiple Client Throughput

Table 5.7 shows the results of the throughput measurements conducted with two clients performing simultaneous file transfers.

d) Roaming Verification

The WaveLAN components successfully completed the roaming test.

4. Lucent Technologies WaveLAN IEEE Components

Currently, the WLAN components produced by Lucent Technologies are IEEE 802.11 compliant. Some of the cards sold operate with variable instantaneous data rates ranging between 11 Mbps, 5.5 Mbps, 2 Mbps, and 1 Mbps. The components evaluated were limited to

Iteration	Direction	Percentage Signal Strength				
		> 50	40-50	30-40	20-30	10-20
1	Client to Server	1140	1050	968	887	553
	Server to Client	1430	1010	908	640	682
2	Client to Server	1160	1050	991	959	287
	Server to Client	1370	989	914	1000	251
3	Client to Server	1110	1010	901	671	316
	Server to Client	1250	916	911	773	288
4	Client to Server	1120	1010	966	789	475
	Server to Client	1240	906	822	762	512
5	Client to Server	1150	1040	960	795	488
	Server to Client	1250	1010	928	651	437
Average Throughput		1222	999.1	926.9	792.7	428.9

Table 5.6: Lucent Technologies WaveLAN Single Client Throughput Measurements (in kbps)

Iteration		Direction	Percentage Signal Strength				
			> 50	40-50	30-40	20-30	10-20
1	Client 1	Client to Server	988	826	904	665	756
		Server to Client	872	626	621	582	532
	Client 2	Client to Server	487	398	304	340	308
		Server to Client	838	711	583	608	540
2	Client 1	Client to Server	1070	810	762	656	752
		Server to Client	1020	612	601	723	622
	Client 2	Client to Server	519	419	324	332	366
		Server to Client	793	825	540	564	598
3	Client 1	Client to Server	1010	851	734	640	938
		Server to Client	1080	678	642	772	758
	Client 2	Client to Server	524	432	310	329	293
		Server to Client	758	669	712	580	644
4	Client 1	Client to Server	1040	756	702	816	791
		Server to Client	804	647	751	728	517
	Client 2	Client to Server	541	455	390	323	353
		Server to Client	862	746	595	624	638
Average Throughput			825.375	653.8125	592.1875	580.125	587.875

Table 5.7: Lucent Technologies WaveLAN Multiple Client Throughput Measurements (in kbps)

those data rates compliant with the IEEE 802.11 standard. These WaveLAN IEEE components are pictured with a WavePOINT-II AP in Fig. 5.10. Their characteristics are described below. [Ref. 15]

- **Type:** DS/SS, IEEE 802.11 Compliant

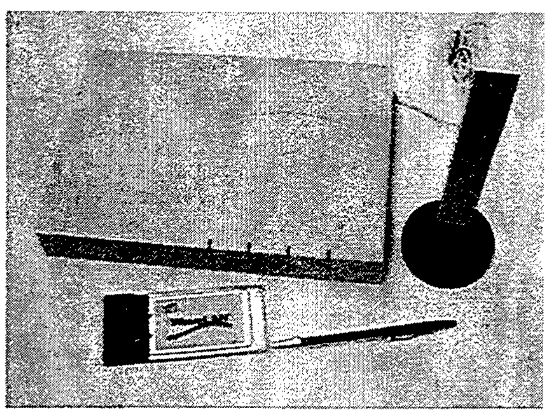


Figure 5.10: Lucent Technologies WaveLAN IEEE Components

- **Advertised Range:** Open Office 1750 ft

  Semi-Open Office 375 ft

  Actual range dependent upon environment.

- **Maximum Data Rate:** 2 Mbps in high signal strength

  1 Mbps in low signal strength

- **PC Card Transmit Power:** 32 mW

- **Consumed Power:** Transmit 330 mA

  Receive 280 mA

  Sleep 9 mA

a) Coverage

Figure 5.11 shows an overlay of the coverage area provided by the WaveLAN IEEE components.

b) Single Client Throughput

Table 5.8 shows the results of the throughput testing conducted at various locations in the subdivisions of coverage shown in Fig. 5.11.

c) Multiple Client Throughput

Table 5.9 shows the results of the throughput measurements conducted with two clients performing simultaneous file transfers.

d) Roaming Verification

The WaveLAN IEEE components successfully completed the roaming test.

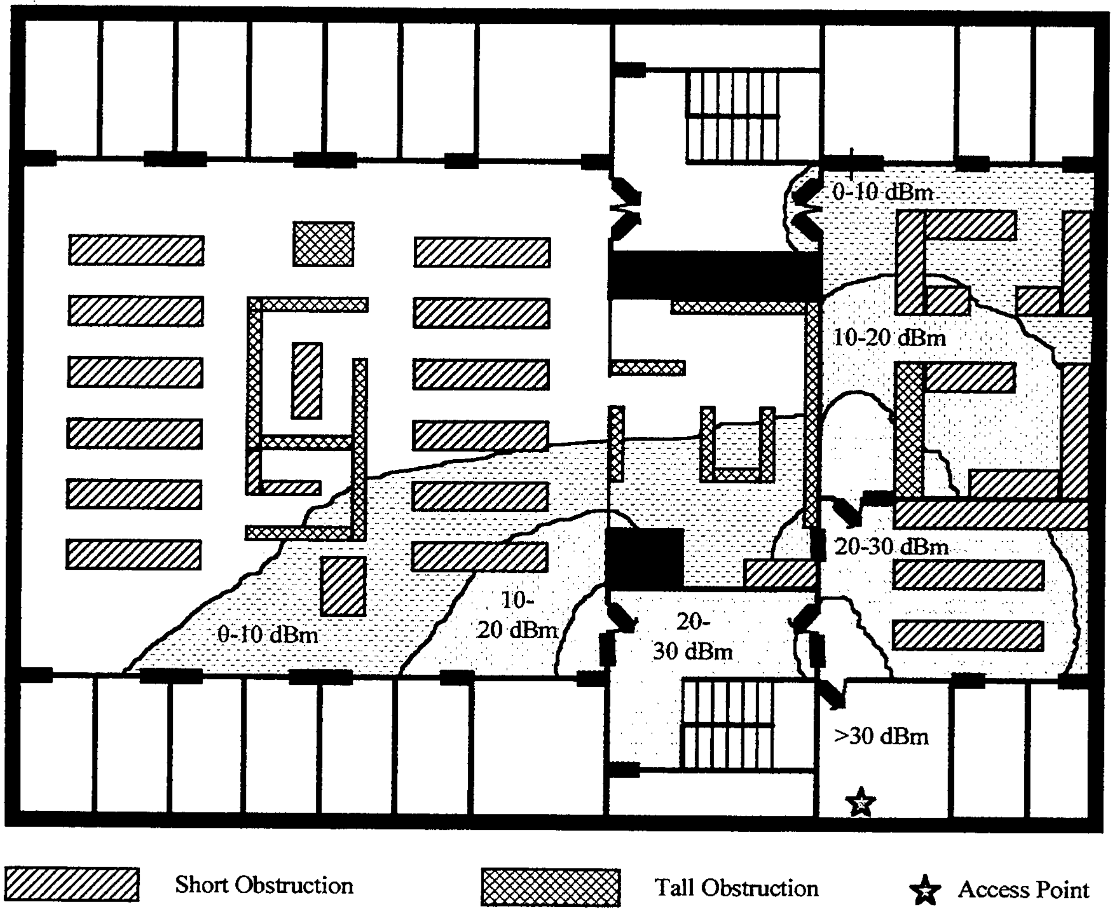


Figure 5.11: Lucent Technologies WaveLAN IEEE Coverage

Iteration	Direction	Signal Strength			
		> 30	20 - 30	10 - 20	0 - 10
1	Client to Server	1270	1160	1160	818
	Server to Client	1510	1230	1200	989
2	Client to Server	1290	1130	1130	966
	Server to Client	1450	1200	1240	651
3	Client to Server	1290	1170	1150	811
	Server to Client	1500	1220	1160	1050
4	Client to Server	1230	1180	1140	1000
	Server to Client	1500	1340	1170	721
5	Client to Server	1200	1180	1150	845
	Server to Client	1420	1270	1230	825
Average Throughput		1366	1208	1173	867.6

Table 5.8: Lucent Technologies WaveLAN IEEE Single Client Throughput Measurements (in kbps)

Iteration		Direction	Signal Strength			
			> 30	20 - 30	10 - 20	0 - 10
1	Client 1	Client to Server	596	629	601	342
		Server to Client	803	692	683	678
	Client 2	Client to Server	581	521	531	487
		Server to Client	863	684	671	693
2	Client 1	Client to Server	607	633	709	642
		Server to Client	783	724	736	636
	Client 2	Client to Server	593	517	551	512
		Server to Client	780	664	753	712
3	Client 1	Client to Server	608	597	628	667
		Server to Client	824	670	686	678
	Client 2	Client to Server	576	539	533	506
		Server to Client	796	702	677	630
4	Client 1	Client to Server	608	597	663	504
		Server to Client	725	661	759	694
	Client 2	Client to Server	520	356	532	463
		Server to Client	689	688	664	638
Average Throughput			684.5	617.125	648.5625	592.625

Table 5.9: Lucent Technologies WaveLAN IEEE Multiple Client Throughput Measurements (in kbps)

C. DISCUSSION OF RESULTS

The results of the testing clearly indicate that the Lucent Technologies WaveLAN IEEE components offer the best performance of the selected devices. An overlay of average single client throughput on the laboratory floor plan is shown in Fig. 5.12 for all components tested. As shown, the coverage area provided by the WaveLAN IEEE components is larger and the throughput is higher. These components were selected for field testing in shipboard environments. The results of these tests are discussed in the next chapter.

The fact that a DS/SS component outperformed the FH/SS components did not come as a surprise. First, recall from Chapter III that the DS/SS components use PSK modulation, which is much more efficient than the FSK modulation used by FH/SS components. The

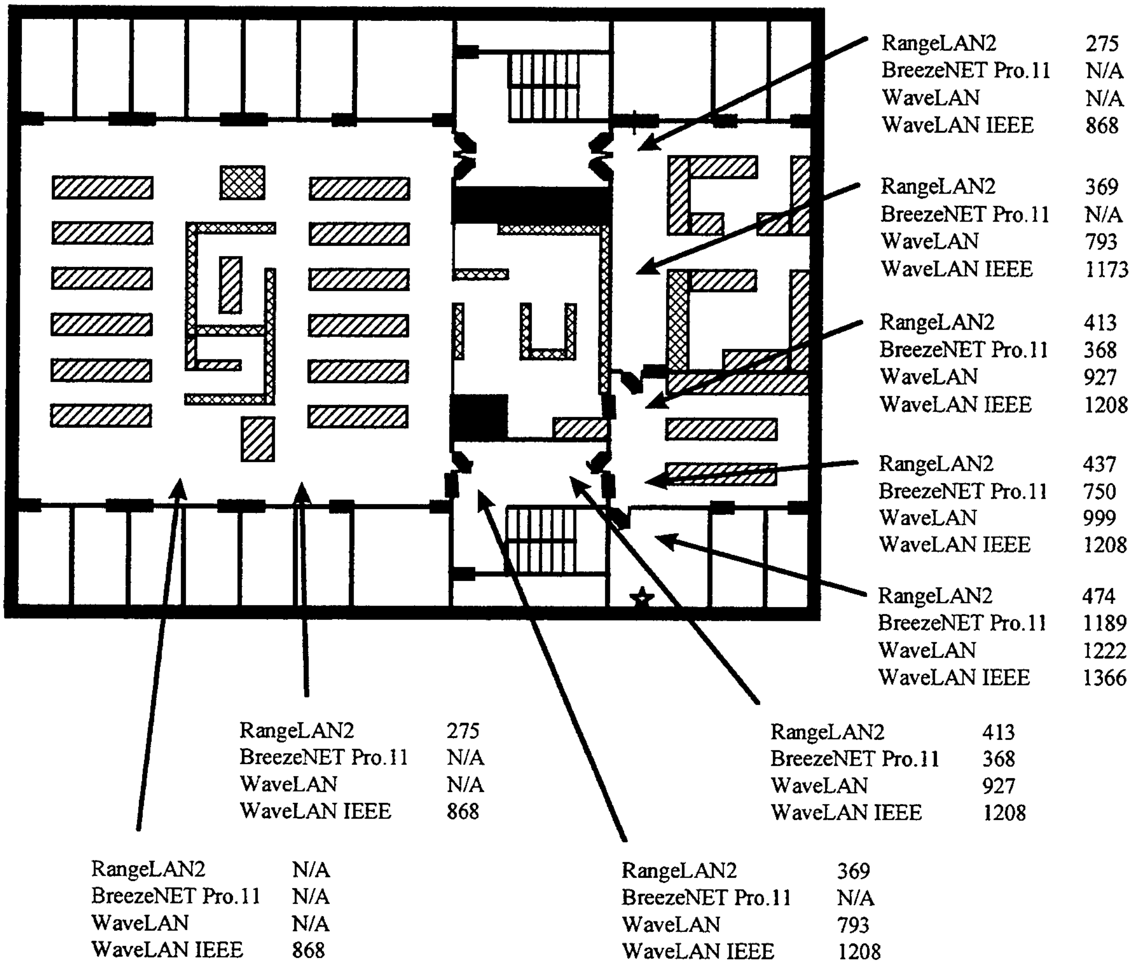


Figure 5.12: Comparative Overlay of Single Client Throughputs for All Components (in kbps)

FH/SS devices require a much higher signal to noise ratio to achieve the same probability of bit error. Secondly, the DS/SS components mitigate the effects of the deep-fade regions of the channel. Errors occur more rarely in DS/SS systems because the signal energy is spread through a wider bandwidth. For FH/SS systems, deep-fade regions of the channel periodically prevent successful transmissions. As the FH/SS system changes frequencies after several hundreds of milliseconds, many packets must be retransmitted due to the multipath channel.

The fact that the WaveLAN IEEE components outperformed the non-compliant WaveLAN components can be attributed to several factors. Most importantly, the WaveLAN components lack the ability to increase received signal strength by reducing the data rate to 1 Mbps. Additionally, the WaveLAN components are older that the WaveLAN IEEE components. Design modifications based upon lessons learned from the earlier components were incorporated into the manufacturing of the IEEE 802.11 compliant components.

VI. FIELD TESTING

In the previous chapter it was determined that the Lucent Technologies WaveLAN IEEE components offered the best performance of those evaluated. These components were then tested in two shipboard environments: the hangarbay of the USS TRUMAN (CVN 75) and onboard the USS MEMPHIS (SSN 691). The field testing procedures and results are discussed in this chapter.

A. USS TRUMAN HANGARBAY WLAN TESTING

WLAN testing was conducted between March 30th and April 2nd, 1999, in the hangarbay of the USS TRUMAN. At that time the ship was located at the Newport News Shipyard in Virginia. No aircraft were present in the hanger during the testing, but the area was cluttered with various trailers and equipment to be used during a maintenance period.

The testing configuration was similar to that used in the laboratory; however, the desktop server was replaced with a Dell Latitude laptop with a 233 MHz Pentium Processor, 32 MB RAM, and Windows 98 (version 4.10) as the operating system. Additionally, a third client was used for multiple client throughput measurement. This device, shown in Fig. 6.1, was a Xybernaut MA IV wearable computer using a Pentium processor running at 200 MHz with 32 MB RAM and using Windows 98 (version 4.10) as the operating system.

1. Coverage

The AP was placed on the starboard side of the hangarbay near frame 120. With the relatively open nature of the hangarbay, only a single AP was required to provide WLAN

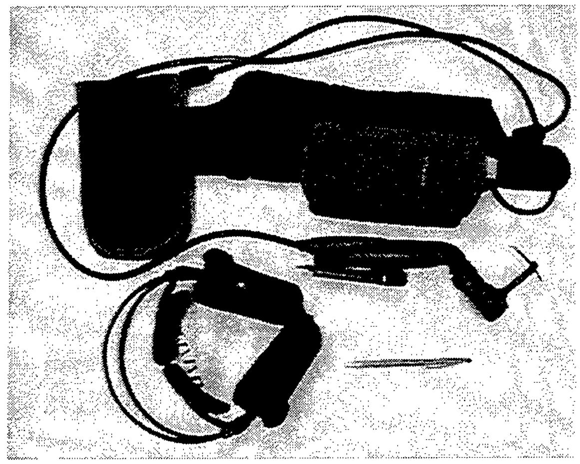


Figure 6.1: Xybernaut MA IV Wearable Computer

coverage to the entire space. The ranges of signal strength provided by the proprietary diagnostic tool are shown in Fig. 6.2.

2. Single Client Throughput

Single client throughput was measured at seven locations throughout the hangarbay. As in the laboratory testing, this throughput was determined using a large file transfer. The average results are shown in Fig. 6.3 and the measured data is provided in Table 6.1.

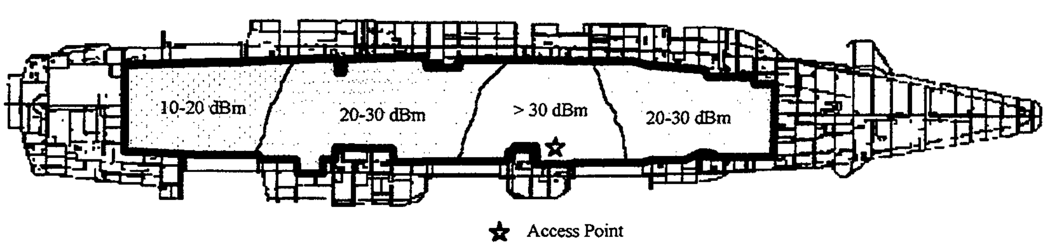


Figure 6.2: Hangarbay Coverage

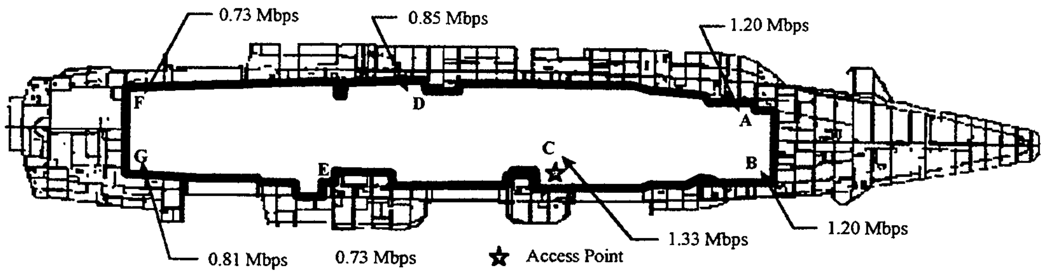


Figure 6.3: Average Single Client Throughput Measurements

Iteration	Direction	Position						
		A	B	C	D	E	F	G
1	Client to Server	1030	1070	1200	635	601	630	638
	Server to Client	1310	1410	1490	1070	586	776	850
2	Client to Server	1060	1030	1150	726	594	737	762
	Server to Client	1340	1280	1540	1200	1000	836	939
3	Client to Server	1150	1020	1090	633	510	524	772
	Server to Client	1310	1390	1500	849	1070	897	907
Average Throughput		1200	1200	1328.333	852.1667	726.8333	733.3333	811.3333

Table 6.1: Single Client Throughput Measurements (in kbps)

3. Multiple Client Throughput

Throughput was then measured using multiple clients. First, throughput was measured using two collocated clients. The average results are shown in Fig. 6.4 with the measured data provided in Table 6.2. Likewise, the results of throughput measurement with two clients at different locations are given in Fig. 6.5 and Table 6.3. Finally, a third client was introduced and the throughput measurements are provided in Fig. 6.6 and Table 6.4.

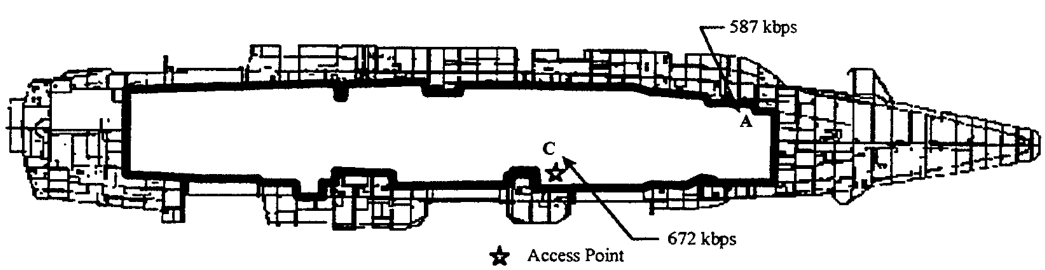


Figure 6.4: Multiple Collocated Client Throughput

Iteration	Client	Direction	Position	
			A	C
1	Client 1	Client to Server	441	485
	Client 2	Client to Server	420	479
2	Client 1	Server to Client	793	833
	Client 2	Server to Client	793	849
3	Client 1	Client to Server	471	511
	Client 2	Client to Server	385	485
4	Client 1	Server to Client	798	882
	Client 2	Server to Client	796	848
5	Client 1	Client to Server	551	653
	Client 2	Server to Client	622	693
6	Client 1	Client to Server	471	639
	Client 2	Server to Client	651	688
7	Client 1	Server to Client	613	736
	Client 2	Client to Server	516	659
8	Client 1	Server to Client	645	649
	Client 2	Client to Server	432	663
Average Throughput			587.375	672

Table 6.2: Multiple Collocated Client Throughput Measurements (in kbps)

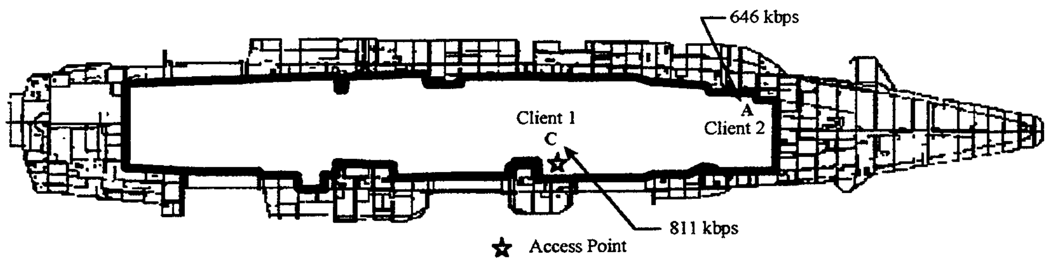


Figure 6.5: Multiple Client Throughput Measurements (Two Clients)

Iteration	Client 1 at 'C'		Client 2 at 'A'	
	Direction	Throughput	Direction	Throughput
1	Client to Server	688	Client to Server	525
2	Server to Client	868	Server to Client	816
3	Client to Server	754	Client to Server	460
4	Server to Client	998	Server to Client	880
5	Client to Server	686	Server to Client	631
6	Client to Server	626	Server to Client	630
7	Server to Client	921	Client to Server	614
8	Server to Client	944	Client to Server	615
Average Throughput		810.625		646.375

Table 6.3: Multiple Client Throughput Measurements (in kbps)

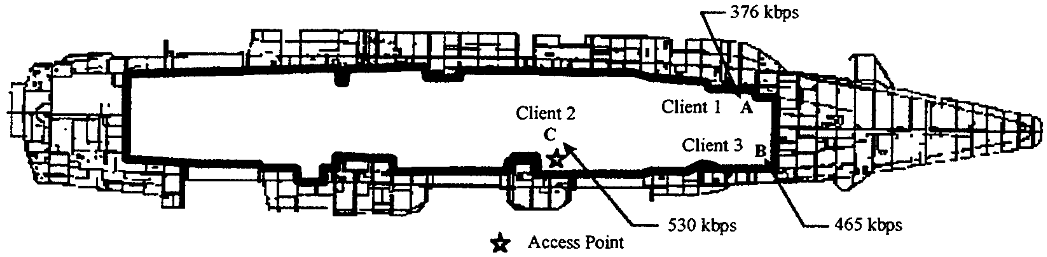


Figure 6.6: Multiple Client Throughput Measurements (Three Clients)

Iteration	Client 1 at 'A'		Client 2 at 'C'		Client 3 at 'B'	
	Direction	Throughput	Direction	Throughput	Direction	Throughput
1	Client to Server	239	Client to Server	468	Client to Server	385
2	Server to Client	507	Server to Client	595	Server to Client	511
3	Client to Server	304	Client to Server	543	Client to Server	385
4	Server to Client	547	Server to Client	617	Server to Client	597
5	Server to Client	409	Client to Server	507	Server to Client	490
6	Client to Server	348	Server to Client	548	Client to Server	470
7	Server to Client	346	Client to Server	402	Client to Server	386
8	Client to Server	321	Server to Client	576	Server to Client	531
9	Server to Client	407	Server to Client	506	Client to Server	432
10	Client to Server	328	Client to Server	535	Server to Client	459
Average Throughput		375.6		529.7		464.6

Table 6.4: Multiple Client Throughput Measurements (in kbps)

4. Discussion of Results

Of all shipboard environments, the hangarbay of a nuclear aircraft carrier probably offers the largest open space. While multipath propagation exists, the hangarbay most likely offers the most benign environment for radio frequency communications. The testing was conducted with no aircraft in the hanger; thus, the results will differ from those measured with the hanger in a normal at-sea condition.

With the large propagation distance of the single AP in the hangarbay, the effects of overlapping AP coverage should be examined. As mentioned in Chapter III, the DS/SS components should offer greater aggregate throughput; however, this has not been verified.

The measured throughput seems to be sufficient. However, more information is required concerning the nature of the proposed network applications and the expected number of wireless clients per AP. The throughput measured was simply for the continuous transfer of large files. This measured data cannot be directly applied to application performance until the statistical characteristics of these proposed applications and the clients are determined.

Following the shipboard testing on the USS TRUMAN, more laboratory testing was conducted using multiple clients and the WaveLAN IEEE components. Throughput was determined using as few as one and as many as five clients. The results of this test are provided in Fig. 6.7. As shown, the aggregate throughput increased as the number of clients increased.

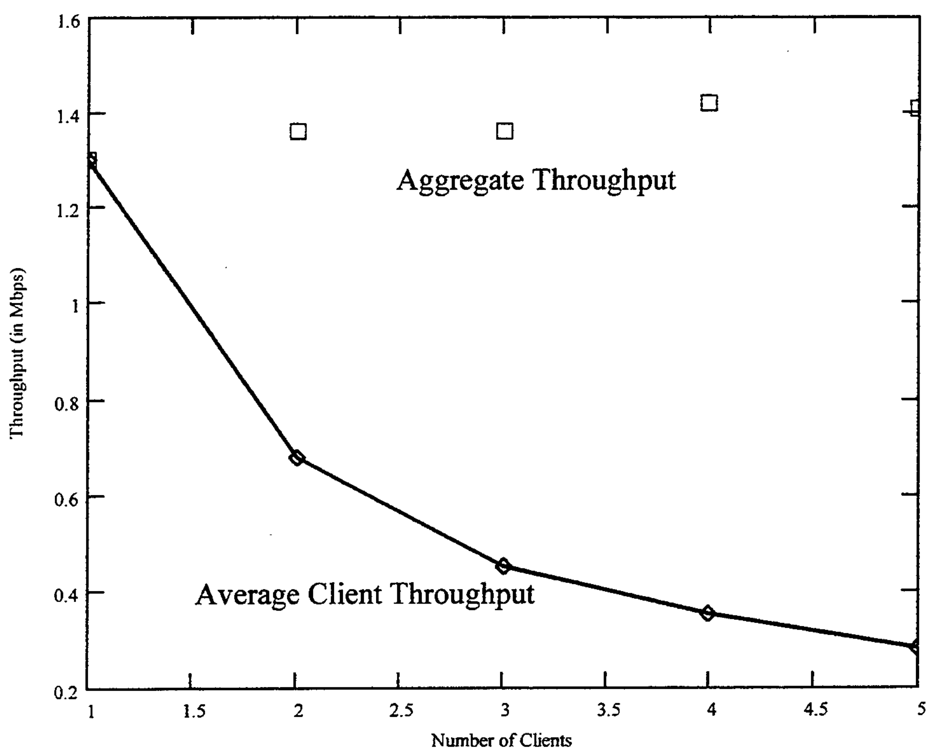


Figure 6.7: Throughput as a Function of Number of Clients

As all clients were within range of each other, data collisions were minimized. The increase in aggregate throughput can be seen as a more efficient utilization of the binary backoff period following transmissions in the CSMA/CA protocol.

B. USS MEMPHIS WLAN TESTING

WLAN testing was conducted between August 4^{th} and 7^{th}, 1999, onboard the USS MEMPHIS, which is designated as the research, development, and testing platform for the Los Angeles class fast attack submarine. During the testing, the ship was pierside at the Naval Submarine Base, New London, Connecticut, with the reactor plant in hot standby.

The purpose of the testing was to determine the number of APs required to provide full WLAN coverage of the inhabitable compartments, propose the locations for the APs to provide optimal coverage, and to measure the throughput provided by these APs.

1. Required Number and Proposed Locations of APs

The Los Angeles class fast attack submarine is divided into two watertight, inhabitable compartments: the Forward Compartment (FC) and the Engine Room (ER). A watertight bulkhead separates these compartments with personnel passage permitted via a watertight door. As this door is normally shut while underway, no radio frequency (RF) signals can propagate from one compartment to the other. Therefore, for complete WLAN coverage of the ship, each compartment must be independently evaluated.

The required number of APs was determined by first establishing an initial position for the first AP. The compartment was then surveyed to determine the range of coverage provided by that AP. The second AP was then positioned to provide overlapping coverage

with the first and to extend the combined area of coverage. This process was repeated until the APs provided complete coverage of the compartment.

In addition to evaluating optimal AP placement with regard to WLAN coverage, logical component placement was considered. The locations chosen are all feasible for permanent AP mounting. Further testing is required to evaluate the long-term impacts of the proposed AP locations. Specifically, testing should be conducted to evaluate the environmental durability of the APs in the harsh conditions offered by normal steaming operations in the ER. The Lucent Technologies WavePOINT-II APs offer a design advantage over competitors in that the AP can be located separately from the antenna.

a) The Engine Room

The ER consists of three levels: Engine Room Upper Level (ERUL), Engine Room Middle Level (ERML), and Engine Room Lower Level (ERLL). ERML actually consists of two physically separated areas: Engine Room Middle Level Aft (ERMLA), also known as Shaft Alley; and Engine Room Middle Level Forward. As with typical marine engine rooms, the compartment consists largely of propulsion and auxiliary equipment. Walkways are provided to allow access to equipment and personnel passage. The outboards and areas between walkways and equipment is largely open to allow the running of piping and cabling. Machinery tends to serve as vertical separations between regions and there are no full bulkheads. This "open" arrangement of the compartment tends to promote greater ranges of multipath RF signals.

The first AP was placed in the forward end of shaft alley slightly port of centerline. This starting point was chosen and the AP was positioned to provide coverage to the aft most portion of the ER. Placing the AP any further forward would degrade the coverage provided to the aft portion of Shaft Alley while placing it any further aft would reduce the coverage range forward for no purpose. The Shaft Alley AP provided coverage to the aft portions of ERUL and ERLL in addition to all of Shaft Alley.

The next two APs were positioned to overlap the Shaft Alley AP while providing WLAN coverage to ERLL and ERUL, respectively. The ERLL AP was placed on the forward end of the Propulsion Lube Oil sump slightly to starboard of centerline. The ERUL AP was placed on the starboard side of the main engine (ME) bedplate, just forward of a computer workstation. These two APs did overlap each other as the reduction gear, main engines, and main condensers tended to discourage multipath propagation. The ERLL AP provided WLAN coverage from the aft portion of ERLL to the turbine generator lube oil space. The ERUL AP provided coverage from the aft portion of ERUL to forward of the ship service turbine generators.

The fourth and final AP for the ER was located in ERMLF centerline above the vital switchboards. The ERMLF AP provided coverage from the turbine generator lube oil space in ERLL and aft of the turbine generators in ERUL to the reactor compartment bulkhead. Additionally, this AP provided coverage in the side passageway to the watertight door.

For each AP location, signal strength was measured. Adjacent APs were located to provide at least 30 dB signal to noise ratio (SNR) in almost all locations. The only

place where 30 dB SNR was not provided was an area of approximately ten square feet on the port side of maneuvering. Table 6.5 below lists the selected locations for APs in the ER.

b) The Forward Compartment

The FC also consists of three levels: Forward Compartment Upper Level (FCUL), Forward Compartment Middle Level (FCML), and Forward Compartment Lower Level (FCLL). Unlike the ER, the FC has complete decks and bulkheads; and, while it does not have the heavy machinery equipment, the spaces are more compartmentalized. As a result, the cross-deck propagation of RF signals was minimized and each deck was treated independently for WLAN coverage.

The first AP was placed in FCML in the forward end of Crew's Mess. This AP provided coverage from the watertight door to approximately the midpoint of aft berthing. A second FCML AP was placed just aft of the Central Air Monitoring Station to provide coverage from forward berthing, ship's office, and the chief's quarters to the wardroom. WLAN coverage was provided to FCLL by placing an AP at the forward end of the torpedo room and another in the Auxiliary Machinery Room at a workbench aft of the R-12 refrigeration plants. Finally, placing an AP in the Combat Systems Electronics Space forward of sonar and another in the aft portion of Control at the BPS-15 radar console covered FCUL.

Access Point	Space	Location
AP 1	ERMLA	Forward End of Shaft Alley, Port of Centerline
AP 2	ERLL	Forward Part of PLO Sump, Stbd of Centerline
AP 3	ERUL	Forward, Stbd Corner of ME Bedplate
AP 4	ERMLF	Centerline, Above Vital AC Switchboards

Table 6.5: Engine Room Access Point Locations

Like the ER, the APs in the FC were located to provide SNR in excess of 30 dB in most areas. The only area where SNR was between 20 and 30 dB was approximately six square feet forward of the Oxygen Generator in the Auxiliary Machinery Room. Table 6.6 below lists the selected locations for APs in the FC.

2. Throughput Measurement

Once the proposed locations for the APs were determined, throughput was measured for varying SNR values for each AP location. For each AP, throughput was measured for file transfers in each direction for three positions where the SNR was greater than 50 dB, three positions where the SNR was between 40 dB and 50 dB, and three positions where SNR was between 30 dB and 40 dB. Because of AP overlap provided at least 30 dB SNR in all but a couple small areas, few throughput tests were conducted with SNR less than 30 dB. Previous laboratory testing predicted a rough correlation between data rate and SNR; however, shipboard testing revealed that, in the submarine environment, little if any correlation existed. The results of the testing are summarized in Table 6.7 below and the actual measurements are included in Tables 6.8 and 6.9. The averages and standard deviations provided in Table 6.7 are

Access Point	Space	Location
AP 5	FCML	Forward End of Crew's Mess
AP 6	FCML	Aft of Central Air Monitoring Station
AP 7	FCLL	Stbd Side of Auxiliary Machinery Room
AP 8	FCLL	Forward End of Torpedo Room
AP 9	FCUL	Stbd Side of Combat Systems Electronics Space
AP 10	FCUL	Aft End of Control on Port Side

Table 6.6: Forward Compartment Access Point Locations

Access Point	Direction	Average (Mbps)	Standard Deviation (Mbps)
AP 1	Server to Client	1.52	0.0237
	Client to Server	1.28	0.0307
AP 2	Server to Client	1.34	0.0495
	Client to Server	1.21	0.0187
AP 3	Server to Client	1.38	0.0303
	Client to Server	1.23	0.0130
AP 4	Server to Client	1.51	0.0193
	Client to Server	1.24	0.0186
AP 5	Server to Client	1.44	0.0279
	Client to Server	1.20	0.0326
AP 6	Server to Client	1.28	0.0340
	Client to Server	1.21	0.0097
AP 7	Server to Client	1.50	0.0300
	Client to Server	1.25	0.0113
AP 8	Server to Client	1.50	0.0273
	Client to Server	1.24	0.0083
AP 9	Server to Client	1.35	0.0397
	Client to Server	1.20	0.0067
AP 10	Server to Client	1.35	0.0319
	Client to Server	1.20	0.0120
ALL	Server to Client	1.42	0.0879
	Client to Server	1.23	0.0307

Table 6.7: Summary of Throughput Testing

for all values of SNR. The measurements taken with SNR between 20 dB and 30 dB are included in the data for AP 4 and AP 7.

3. Discussion of Results

Regardless of signal strength, the WLAN components provided relatively consistent throughput. Thus, with access points located as specified in Table 6.5 and Table 6.6, clients can expect a throughput between 1.23 Mbps and 1.43 Mbps depending on the direction of data transfer. As illustrated in Fig. 6.7, the aggregate throughput should increase as the number of clients increases provided that all clients are within range of one another. Additionally, as

Access Point	Data Run	Direction	Signal to Noise Ratio (SNR)			
			> 50 dB	50-40 dB	40-30 dB	30-20 dB
AP 1	1	Server to Client	1.53	1.53	1.53	
		Client to Server	1.36	1.28	1.26	
	2	Server to Client	1.53	1.53	1.52	
		Client to Server	1.27	1.27	1.28	
	3	Server to Client	1.52	1.54	1.46	
		Client to Server	1.28	1.27	1.28	
AP 2	1	Server to Client	1.34	1.39	1.4	
		Client to Server	1.22	1.23	1.19	
	2	Server to Client	1.35	1.24	1.33	
		Client to Server	1.22	1.2	1.17	
	3	Server to Client	1.37	1.3	1.31	
		Client to Server	1.21	1.2	1.22	
AP 3	1	Server to Client	1.39	1.4	1.31	
		Client to Server	1.23	1.24	1.21	
	2	Server to Client	1.41	1.36	1.37	
		Client to Server	1.25	1.23	1.23	
	3	Server to Client	1.37	1.39	1.4	
		Client to Server	1.23	1.25	1.22	
AP 4	1	Server to Client	1.51	1.53	1.53	1.5
		Client to Server	1.25	1.26	1.24	1.22
	2	Server to Client	1.47	1.5	1.53	1.51
		Client to Server	1.22	1.2	1.26	1.24
	3	Server to Client	1.48	1.51	1.5	1.49
		Client to Server	1.26	1.23	1.24	1.23

Table 6.8: Engine Room Throughput Measurements (in Mbps)

Access Point	Data Run	Direction	Signal to Noise Ratio (SNR)			
			> 50 dB	50-40 dB	40-30 dB	30-20 dB
AP 5	1	Server to Client	1.42	1.48	1.4	
		Client to Server	1.22	1.2	1.19	
	2	Server to Client	1.44	1.44	1.46	
		Client to Server	1.12	1.22	1.21	
	3	Server to Client	1.46	1.42	1.48	
		Client to Server	1.21	1.21	1.23	
AP 6	1	Server to Client	1.3	1.25	1.28	
		Client to Server	1.21	1.21	1.2	
	2	Server to Client	1.24	1.33	1.26	
		Client to Server	1.22	1.22	1.19	
	3	Server to Client	1.34	1.28	1.28	
		Client to Server	1.21	1.21	1.2	
AP 7	1	Server to Client	1.52	1.49	1.5	1.46
		Client to Server	1.24	1.25	1.25	1.26
	2	Server to Client	1.52	1.48	1.53	1.45
		Client to Server	1.25	1.26	1.26	1.22
	3	Server to Client	1.53	1.52	1.45	1.49
		Client to Server	1.25	1.26	1.25	1.25
AP 8	1	Server to Client	1.52	1.5	1.46	
		Client to Server	1.24	1.24	1.25	
	2	Server to Client	1.54	1.48	1.51	
		Client to Server	1.25	1.24	1.23	
	3	Server to Client	1.47	1.51	1.53	
		Client to Server	1.25	1.23	1.25	
AP 9	1	Server to Client	1.35	1.32	1.28	
		Client to Server	1.2	1.21	1.2	
	2	Server to Client	1.4	1.35	1.38	
		Client to Server	1.2	1.21	1.2	
	3	Server to Client	1.38	1.38	1.31	
		Client to Server	1.21	1.2	1.19	
AP 10	1	Server to Client	1.35	1.36	1.34	
		Client to Server	1.21	1.19	1.21	
	2	Server to Client	1.39	1.32	1.34	
		Client to Server	1.2	1.22	1.2	
	3	Server to Client	1.4	1.3	1.33	
		Client to Server	1.21	1.2	1.18	

Table 6.9: Forward Compartment Throughput Measurements (in Mbps)

discussed in Chapter III, collocating three APs with sufficient channel frequency separation will provide a further increase in aggregate throughput.

As discussed in the USS TRUMAN testing, this measured throughput cannot be directly applied to predict application performance until the characteristics of the applications are known. However, the number of clients for each AP should be much lower for submarine based WLANs than for hangarbay WLANs. Provided that network applications are reasonably efficient in their network usage, the WaveLAN IEEE components are fully capable of providing a wireless adjunct to an existing LAN.

THIS PAGE INTENTIONALLY BLANK

VII. CONCLUSIONS

The goal of this thesis was to evaluate commercially available wireless networking components and determine the feasibility of employing WLANs onboard naval vessels. The results of the testing conducted in Chapters V and VI show that the current technology meets the current needs of the navy.

A. DISCUSSION

Current, commercially available, wireless networking components are ready for employment onboard naval vessels. The results of the laboratory testing described in Chapter V show that the DS/SS components will generally outperform their FH/SS counterparts. Figure 7.1 shows an overhead view of the laboratory environment and provides a comparison of the average, single client throughput measurements for each of the components evaluated. Clearly, the Lucent Technologies WaveLAN IEEE components provide the best performance. Therefore, the shipboard testing described in Chapter VI was conducted using the WaveLAN IEEE components.

Although an IEEE 802.11 compliant device was selected as the best performer, the requirement that components selected for naval use strictly adhere to this standard is questionable. As always, strict compliance to international standards usually comes at the cost of performance. However, the IEEE 802.11 standard is one step towards multi-vendor compatibility, a feature that is very attractive in the Department of Defense acquisition process.

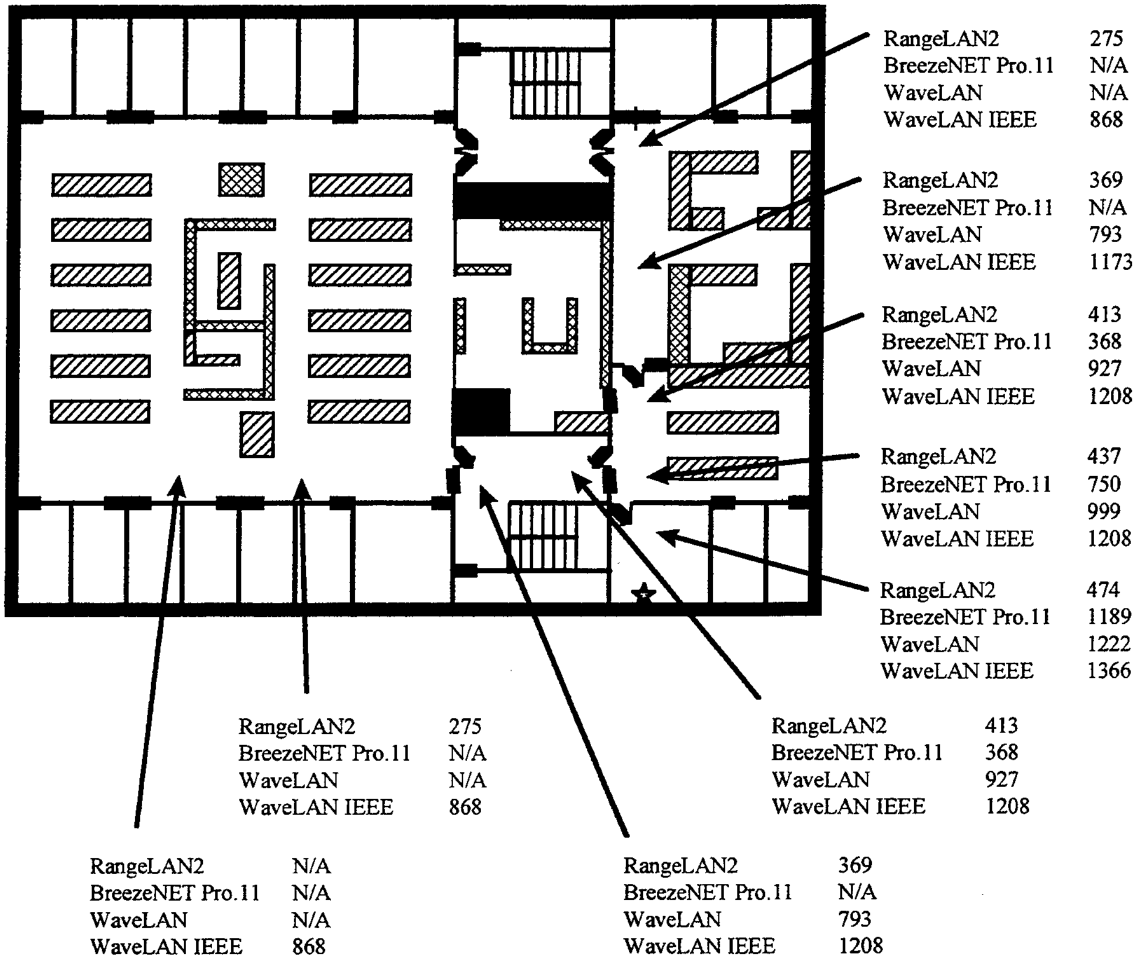


Figure 7.1: Laboratory Results for Single Client Throughput Measurements (in kbps)

The shipboard testing described in Chapter VI evaluated the performance of the WaveLAN IEEE components onboard naval vessels. First, the wireless components were evaluated in the hangarbay of the USS TRUMAN. Figure 7.2 shows the coverage and the average single client throughput. As shown, a single AP provides coverage for the entire hangarbay. The relatively open environment offered by the hangarbay increases the effective range of the WLAN components but, due to mutual interference, reduces the number of APs that can be located in that space. As discussed in Chapter IV, the FCC restriction on the

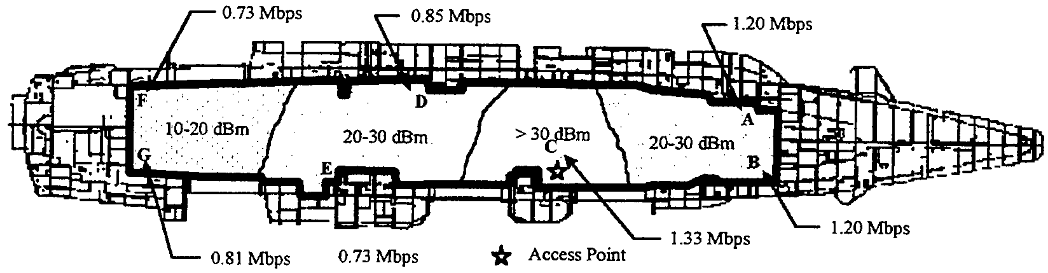


Figure 7.2: Results of Testing Conducted Onboard USS TRUMAN

available bandwidth in the ISM band limits the number of non-interfering, collocated APs to three. The WaveLAN IEEE components were also evaluated onboard the USS MEMPHIS, a Los Angeles class submarine. In addition to performing single client throughput tests, the required number and optimum locations of APs to provide complete WLAN coverage was determined. As discussed in Chapter VI, the Engine Room required fewer APs than the Forward Compartment. The recommended locations for APs and the average single client throughput measurements are provided in Table 7.1.

FORWARD COMPARTMENT		
Access Point	**Space**	**Location**
AP 5	FCML	Forward End of Crew's Mess
AP 6	FCML	Aft of Central Air Monitoring Station
AP 7	FCLL	Stbd Side of Auxiliary Machinery Room
AP 8	FCLL	Forward End of Torpedo Room
AP 9	FCUL	Stbd Side of Combat Systems Electronics Space
AP 10	FCUL	Aft End of Control on Port Side
Average Throughput		1.31 Mbps
ENGINE ROOM		
Access Point	**Space**	**Location**
AP 1	ERMLA	Forward End of Shaft Alley, Port of Centerline
AP 2	ERLL	Forward Part of PLO Sump, Stbd of Centerline
AP 3	ERUL	Forward, Stbd Corner of ME Bedplate
AP 4	ERMLF	Centerline, Above Vital AC Switchboards
Average Throughput		1.34 Mbps

Table 7.1: Results of Testing Conducted Onboard USS MEMPHIS

This thesis merely examines if a wireless network is feasible. Adequate information is provided to install a wireless network onboard a Los Angeles class submarine that provides sufficient throughput for most applications. However, the success of a network is not determined by throughput. If the navy decides to employ wireless networks, sufficient resources must be devoted to ensure that quality software is offered that meets the users' needs.

B. RECOMMENDATIONS FOR FURTHER STUDY

Computer related technologies continue to increase at rates that meet or exceed Moore's Law. Therefore, there are many recommendations for further study.

1. Wireless Component Evaluation

The field of wireless networking is constantly evolving. The components evaluated in this thesis will be outdated in less than six months. The IEEE 802.11 standard is evolving to include higher data rate systems. Currently, DS/SS components compiant with the new IEEE 802.11b standard operate at 11 Mbps [Ref. 16]. Additionally, FH/SS equipment manufacturers are developing 24 Mbps components that operate in the 5 GHz frequency range of the ISM band [Ref. 17]. It should not be assumed that these new components will offer the same shipboard performance as their lower data rate counterparts. Constant evaluation of new components should be conducted to determine which systems best suit the needs of the navy.

2. Mobile Computer Evaluation

Naval ships offer a rigorous environment for computer systems. During the course of the testing involved in this thesis, several expensive components broke down. One viable alternative to expensive, robust computer systems is the relatively new Windows CE devices. These devices offer solid construction with no internal moving parts. They are relatively inexpensive and disposable. However, they do not offer the same features as other mobile computers. The relative pros and cons of these low cost Windows CE devices should be compared to those offered by more robust mobile systems.

3. Battle Group Integration

The components examined in this thesis offer mobility to network clients. While they were only examined in an infrastructure mode, these wireless components can operate without interface to a conventional LAN in an ad-hoc mode. The protocols used in this ad-hoc mode may prove adaptable to other means of communication. Thus, integrated into a secure naval communications system, similar protocols may produce a more efficient means to share information between naval ships operating in a battle group.

4. Software Prototyping

The single factor which will determine the successful employment of a computer system is the software provided. A common complaint regarding naval computer systems is that the offered software fails to meet the warfighter's needs. Various, high quality software applications need to be developed to make any network installation feasible. Additionally, these applications must be designed to support mobile computers with various capabilities.

THIS PAGE INTENTIONALLY BLANK

LIST OF REFERENCES

1. Stallings, William, *Data and Computer Communications*, Prentice Hall, Upper Saddle River, NJ, 1997.

2. Interview with Clark Robertson, Professor, Naval Postgraduate School, Monterey, California, 17 May 1999.

3. Sklar, B., "Rayleigh Fading Channels in Mobile Digital Communication Systems Part I: Characterization," *IEEE Communications Magazine*, July 1997.

4. Sklar, B., "Rayleigh Fading Channels in Mobile Digital Communication Systems Part II: Mitigation," *IEEE Communications Magazine*, July 1997.

5. Simon, Marvin K., Jim K. Omura, Robert A. Scholtz, and Barry K. Levitt, *Spread Spectrum Communications Handbook*, McGraw-Hill, Inc., New York, NY, 1994.

6. Federal Communications Commission, Part 15 Rules, Washington, D.C., March 1999. http://www.fcc.gov/oet/info/rules/

7. Interview with Clark Robertson, Professor, Naval Postgraduate School, Monterey, California, 16 August 1999.

8. Institute of Electrical and Electronic Engineers, Inc., *IEEE Standard 802.11-1997*, Institute of Electrical and Electronic Engineers, Inc., New York, NY, 1997.

9. Kamerman, A., "Spread Spectrum Techniques Drive WLAN Performance," *Microwaves & RF*, September, 1996, pp. 109-114.

10. BreezeCOM Ltd., *BreezeNET PRO.11 User's Guide*, BreezeCOM Ltd., Carlsbad, CA, 1998.

11. Andren, C., "A Comparison of Frequency Hopping and Direct Sequence Spread Spectrum Modulation for IEEE 802.11 Applications at 2.4GHz," www.semi.harris.com/whatsnew/dsss/index.htm

12. Tanenbaum, Andrew S., *Computer Networks*, Prentice Hall, Upper Saddle River, NJ, 1996.

13. Proxim, Inc., *RangeLAN2 7400 User's Guide*, Proxim, Inc., Mountain View, CA, 1997.

14. Lucent Technologies, Inc., *WaveLAN / PCMCIA Card User's Guide*, Lucent Technologies, Inc., The Netherlands.

15. Lucent Technologies, Inc., *IEEE 802.11 WaveLAN User's Guide*, Lucent Technologies, Inc., The Netherlands.

16. Lucent Technologies, Inc., "WaveLAN Wireless Network Now Compliant with New IEEE High-Speed Standard," http://www.wavelan.com/news/news.html?id=69, October 1999.

17. Proxim, Inc., "Proxim's High Speed Products," http://www.proxim.com/products/highspeed/index.shtml, April 1999.

INITIAL DISTRIBUTION LIST

No. Copies

1. Defense Technical Information Center 2
   8725 John J. Kingman Rd., STE 0944
   Ft. Belvoir, VA 22060-6218

2. Dudley Knox Library 2
   Naval Postgraduate School
   411 Dyer Rd.
   Monterey, CA 93943-5101

3. Chairman, Code EC 1
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, CA 93943-5121

4. Professor Xiaoping Yun, Code EC/YX 3
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, CA 93943-5121

5. Professor John McEachen, Code EC/MJ 1
   Department of Computer Science
   Naval Postgraduate School
   Monterey, CA 93943-5121

6. Mr. Steve Lose 2
   Program Executive Officer, Submarines
   PMS 450T2, NC2 5W64
   2531 Jefferson Davis Highway
   Arlington, VA 22242-5168

7. Mr. Gary Lacombe 2
   171 Branch Hill Rd
   Preston, CT 06365

8. LT Mark Matthews 2
   109 Bay Ridge
   Chocowinity, NC 27817